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TRANSPARENCY DURABILITY TEST CRITERIA

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13. ABSTRACT *(Maximum 200 words)*
The focus of the Transparency Durability Test Criteria Program was to develop a durability test methodology for aircraft transparency systems which includes laboratory coupon durability testing and field service data acquisition. These areas were used to advance the development, measurement, and comparison of coupon testing to in-service aircraft transparency durability, where durability is defined as the continued ability of the transparency to meet specified performance requirements. Summaries of coupon tests and field service data acquisition and analysis are reported. New coupon tests introduce in this program include combined testing such as dust erosion and craze testing. A relationship between craze resistance and rain erosion exposure was also demonstrated. Identification of technology voids and other approaches to improve durability assessment are discussed. This report also provides a summary of the major accomplishments of the program, including the core durability task and additional tasks including alternate QUV cycles, durability of coatings, and improved bolt hole durability.

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Foreword

The work reported herein was performed by the Aerospace Mechanics Division of the University of Dayton Research Institute (UDRI), Dayton, Ohio, for the Flight Dynamics Directorate of Wright Laboratory under Air Force Contract F33615-90-C-3410. The work was conducted during the period December 1990 to February 1996. UDRI supervision was provided by Mr. Blaine S. West, Head, Aerospace Mechanics Division, and Mr. Michael P. Bouchard, Head, Structures Group. Messrs. Thomas J. Whitney and Daniel R. Bowman were the Principal Investigators. The Air Force Program Manager was Mr. Richard A. Smith, WL/FIVE-1.

The authors wish to acknowledge a number of individuals who contributed significantly to the effort: Mr. Timothy Montavon, sample preparation and testing; Dr. Alan P. Berens, field data and test data analysis; Mr. Robert Oeding, dust erosion facility consultant; Mr. Malcolm Kelley, WL/FIVE-1, field data collection; and Mary Lee Deford, Texstar, Inc., field data and service-aged coupon collection.

1. Introduction

1.1. Background

This document is the Final Report for the Transparency Durability Test Criteria Program. The focus of the Transparency Durability Test Criteria Program was to develop a durability test methodology for aircraft transparency systems which includes laboratory coupon scale durability testing, full scale durability testing, and field service data acquisition. These three areas were used to advance the development, measurement, comparison, and prediction of actual in-service aircraft transparency durability, where durability is defined as the continued ability of the transparency to meet specified performance requirements. A goal of the Air Force is that future aircraft transparency systems have a 4-year service life (on the aircraft). This program was conducted to provide better tools for the transparency community to understand, predict, and increase transparency durability.

The recommendations in this report are based on the Phase I and Phase II Methodology Reports [1, 2], analysis of transparency durability testing and field service data acquisition information from the literature survey [3] and the durability testing and field service data review [4], the coupon scale test plan [5], and the analysis of results from coupon tests reported herein.

1.2. Objective

The objectives of this report are to provide a summary of the third phase of the Transparency Durability Test Criteria Program, including the results of coupon scale testing and field service data acquisition and analysis; to summarize the major accomplishments of the program, including the core durability task and additional tasks; and to recommend the next steps required for developing a predictive transparency durability tool. This report also summarizes and discusses the integration of and correlation between coupon scale durability testing and actual field service performance (as measured by actual field service data), and alternatives to the durability approach and philosophy used in this program.

1.3. Scope

This report is the final of three similar reports, one for each phase of this contract. The coupon test methods described in this report and the two previous methodology reports are

applicable to various transparency systems which incorporate glass, plastic, and metallic and nonmetallic coatings.

2. Transparency Durability Methodology

The overall methodology of predicting aircraft transparency durability is based on Figure 1. The first step in assessing durability is coupon scale testing. If coupon scale testing indicates that materials perform adequately, then full scale component durability testing is conducted. If full scale durability testing indicates that the component will be adequately durable, then the transparency design is ready for field service. If coupon scale or full scale testing reveals durability problems with a design, the design can be changed. If field service data reveals a problem, changes can be made not only to the transparency design, but the entire methodology, which includes choice of coupon scale tests and interpretation of the results of the coupon scale tests. Coupon scale and full scale durability testing are conducted with correlation made between both types of testing and field service data. The whole process is iterative and can change continuously as it is used to reflect lessons learned and improvements in testing and interpretation of test results.

The details of each of the durability methodology components (coupon scale testing, full scale testing, and field service data collection and analysis) must be identified and recommendations made for choosing test techniques and evaluating results. However, the parameters for and the interrelationships between the components are often not well defined. The system must improve with implementation. This methodology is a general one which could be applied to any transparency system. The exact choice of tests and interpretation of results is system specific. The choice of tests and analysis of results for a new system must be based on experience with similar systems.

The key to identifying and recommending specific aspects of durability testing is accurately identifying and characterizing the environment in which the transparency exists. Clearly, a transparency system is subject to temperature variations, radiation (ultraviolet wavelengths being the most critical), humidity, chemical contact, and a variety of other types of environmental exposure. General severity levels of environmental parameters *can* be used to qualitatively assess expected service life. For instance, a transparency in a cloudy environment with consistent 60°F temperature and 40% relative humidity will very likely last longer than an identical transparency in a sunny environment with 90°F temperature and 90% relative humidity due to the degrading effects of the high levels of these parameters. However, as the results of this program demonstrate, it is extremely difficult to predict exactly how long either transparency will remain in service based on general weather data alone.

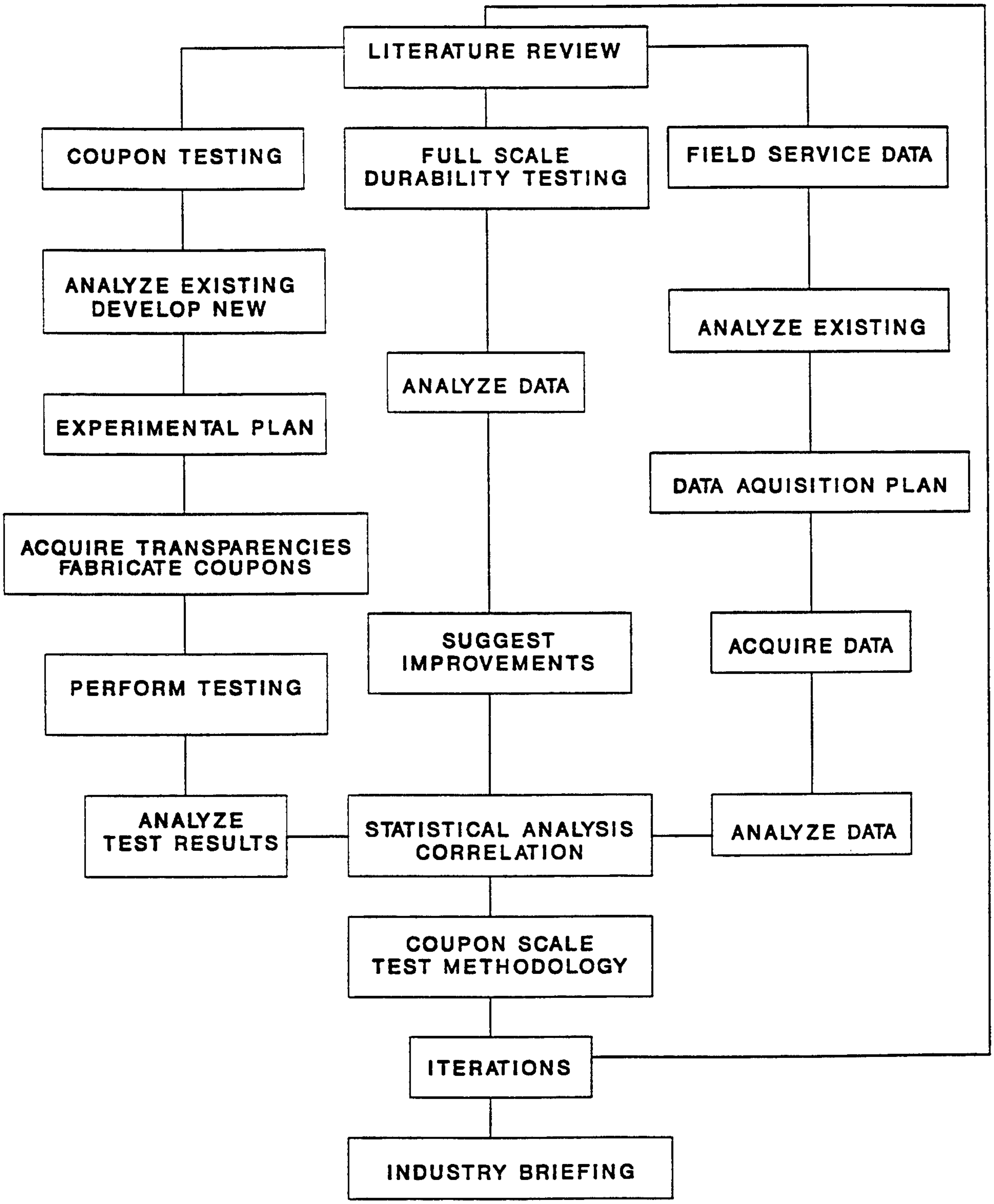


Figure 1. Aircraft Transparency Durability Prediction.

Laboratory testing based on duplicating basic weather parameters simply does not correlate well with field service data. It is critical to establish the precise exposure history of the transparency to identify the factors that are responsible for ending useful service life.

2.1. Coupon Testing

Given a degree of confidence that the exposure conditions and circumstances surrounding failure have been adequately identified and characterized, those conditions and circumstances must be accurately reproduced in the laboratory. In most instances, replication is not difficult for one, two, or three parameters when actual conditions are uniform. However, when many parameters that are changing rapidly over the course of the test must be reproduced, difficulty in control may occur. Note in such cases where it may be tempting to "average" rapidly changing parameters for easier control, doing so might invalidate the test if the "peaks" in the parameters are the critical elements in exposure environment.

One of the most difficult aspects of exposure replication in laboratory testing is correctly accelerating conditions such that failures in the lab occur exactly as they do in the field, only quicker. It can be difficult to correlate accelerated and non-accelerated laboratory tests, which are presumably tightly controlled, much less accelerated laboratory tests and field data. Durability metrics as a function of time-at-exposure and exposure level tend to be very non-linear. For example, laboratory craze data is accelerated by increasing the applied mechanical load. Good craze resistance at high stress for a short amount of time is considered equivalent to good craze resistance at low stress for long amount of time. However, *very* long term field and laboratory data have shown that craze does in fact occur, despite indications to the contrary in accelerated testing [6].

Laboratory scale coupons must be fabricated to duplicate essential features of the component as closely as possible. Material type and quality, processing, surface quality, machining, and handling characteristics inherent in the component must be replicated in the coupon. For example, interior coating failures on the 350-knot F-16 canopy have resulted in short service lives for some parts. The manufacturer has demonstrated good coating durability on laboratory-scale flat coupons. However, coatings applied to full-scale contoured parts have poor durability as evidenced by field failures [7]. Clearly, the process in the laboratory for coating flat coupons does not accurately reproduce the process on the production line.

2.2. *Full-Scale Testing*

Full scale testing is conducted to verify that the transparency will withstand system level failures which cannot be reproduced at the coupon level. Full scale failure modes include vibration induced failure, structural failure due to pressure and thermal gradients, and failure due to manufacturing flaws (such as incorrect surface preparation during assembly of edging and fastener bushings). The test articles should be actual transparencies manufactured in the same manner using the same techniques as transparencies intended for field use.

As with coupon-scale testing, accurate duplication of the exposure environment is essential for assessing durability and replicating failure modes. Precise replication can be difficult and expensive. For instance, the orientation of the aircraft with respect to the sun influences the amount of radiation incident on the transparency. The storage or ground location of the aircraft (tarmac, hangar, etc.) affects radiant heat transfer to and from the transparency, which affects cockpit solar heating and external cooling rates. The pressure differential between internal static pressure and external stagnation pressure varies considerably with aircraft velocity, creates stress, and influences craze resistance and fatigue cracking. The test frame, therefore, must represent accurately the mass and stiffness of the fuselage in the vicinity of the transparency. Only in this manner may structural vibration and heat transfer characteristics of the transparency system be precisely replicated in a full scale test.

With difficulties experienced in replicating the exposure environment, full scale testing is sometimes considered cost-prohibitive, with a high cost-to-benefit ratio. Wright Laboratory closed their full-scale facility in 1992. Full-scale facilities still exist at PPG Industries in Huntsville, Alabama, and at Sierracin/Sylmar Corporation in Sylmar, California. However, these facilities have limited capabilities in comparison to the now closed Wright Laboratory facility.

Due to the expense and sometimes poor correlation between full-scale testing and actual in-service performance, full-scale testing is often not undertaken. The best and often used approach in this case is to conduct an Operational Test and Evaluation (OT&E) program after the completion of coupon-scale testing. A recommended duration for flight testing of prototype systems is two years or more. Various administrative, technical, and procurement pressures often shorten this duration to one year or less.

2.3. *Methodology Validation*

The general methodology framework discussed above is a "common sense" approach to assessing the durability prospects for a new transparency material or system. The approach is based on observation of the performance of materials and systems in tests which are meant to duplicate the exposure environment. In this way, materials and systems which are the most durable are selected for use, and the prospects of re-design after the start of production are diminished.

Practically speaking, however, the true test for durability is how a transparency performs in the field. Once durability testing has ended and parts are in the field, the effectiveness of the testing must be assessed. If durability assessment indicates an expected service life of four years and the parts in fact remain in service for 4 years, the methodology has been validated. When durability tests indicate a service life of 4 years, but parts are removed after 6 months, the methodology must be reevaluated for completeness and accuracy. Evaluation of the methodology starts with the collection of field data.

The objective of field data collection should be to answer a number of questions. What are the relevant failure modes? Have these failures been replicated by the testing? What are the circumstances of failure? Were installation TO's and maintenance procedures followed? Did unusual weather-related events outside the scope of testing occur which reduced transparency durability? Did the testing accurately represent the exposure environment?

Field data collection need not start with the end user. Perhaps the test methods used are adequate but the transparency material or system itself is faulty. Does the manufacturer's QC documentation indicate any unusual events during processing? Was the material used the correct grade and quality? As noted above, the durability methodology must replicate the material and system as closely as possible. Changes to either will most likely necessitate changes to the test methodology.

A wide variety of factors exist which affect transparency durability. Identifying the factor(s) which render durability testing inaccurate is like the work of a detective, following clues and gathering evidence that points to the circumstances for which durability testing has not accounted. "Circumstances" include, but are not limited to, a lack of basic understanding of how materials react to various environments; lack of understanding of the environment itself; inaccurate acceleration of an exposure environment; lot-to-lot variation in materials; and invalid

methods of data correlation. Each factor is a link in the durability assessment chain. A break in any link of the chain might render the assessment invalid.

3. Coupon Scale Durability Testing

3.1. Coupon Scale Methodology

The philosophy of the coupon scale testing is to conduct tests with specimens from new and artificially weathered transparencies, evaluate changes in measured properties as a result of artificial weathering and conditioning, and correlate those changes to changes in measured properties from service-aged coupons. These tests are then directly or indirectly related to the failure mode of interest. Degradation under artificial weathering conditions was the subject of Phase I coupon scale testing. Changes in measured properties of service-aged transparencies was the focus of Phase II testing.

Several approaches exist for correlating artificially aged and service aged coupon test results. Figure 2 is one example of how a given test property might degrade with time under ideal in-service conditions. Field service data are used to indicate the range of service lives at which failure has occurred. Projecting the range of service lives onto the degradation curve yields a range of property values for transparencies which can be called "at risk" for failure due to the failure mode represented by the test.

The duration of artificial exposure required to duplicate "at risk" property values is obtained by comparing the range of property values for failed transparencies to a degradation curve for artificially conditioned samples. As shown in Figure 3, artificially conditioned coupon data should behave similarly to service aged coupon data. Several of the Phase I coupon test results exhibited behavior suggesting such property degradation. Projecting the property value range onto the degradation curve of Figure 3 yields a range of simulated exposure time required to achieve the property value range for "at risk" transparencies. Coupons with property values in this range indicate that the associated transparency will be "at risk" for failure due to the failure mode associated with the particular test.

The assumptions made and the discrepancies which will result from this approach are worth noting. The consistency of conditioning exposure will be better for the artificially aged specimens than for the service aged specimens, since no two service aged transparencies are exposed to exactly the same environment or conditioning. Until proposals for instrumenting transparencies with micro-sensors (to monitor actual exposure history) are implemented, the best measures of in-service conditioning are time on the airplane, known as service life, and

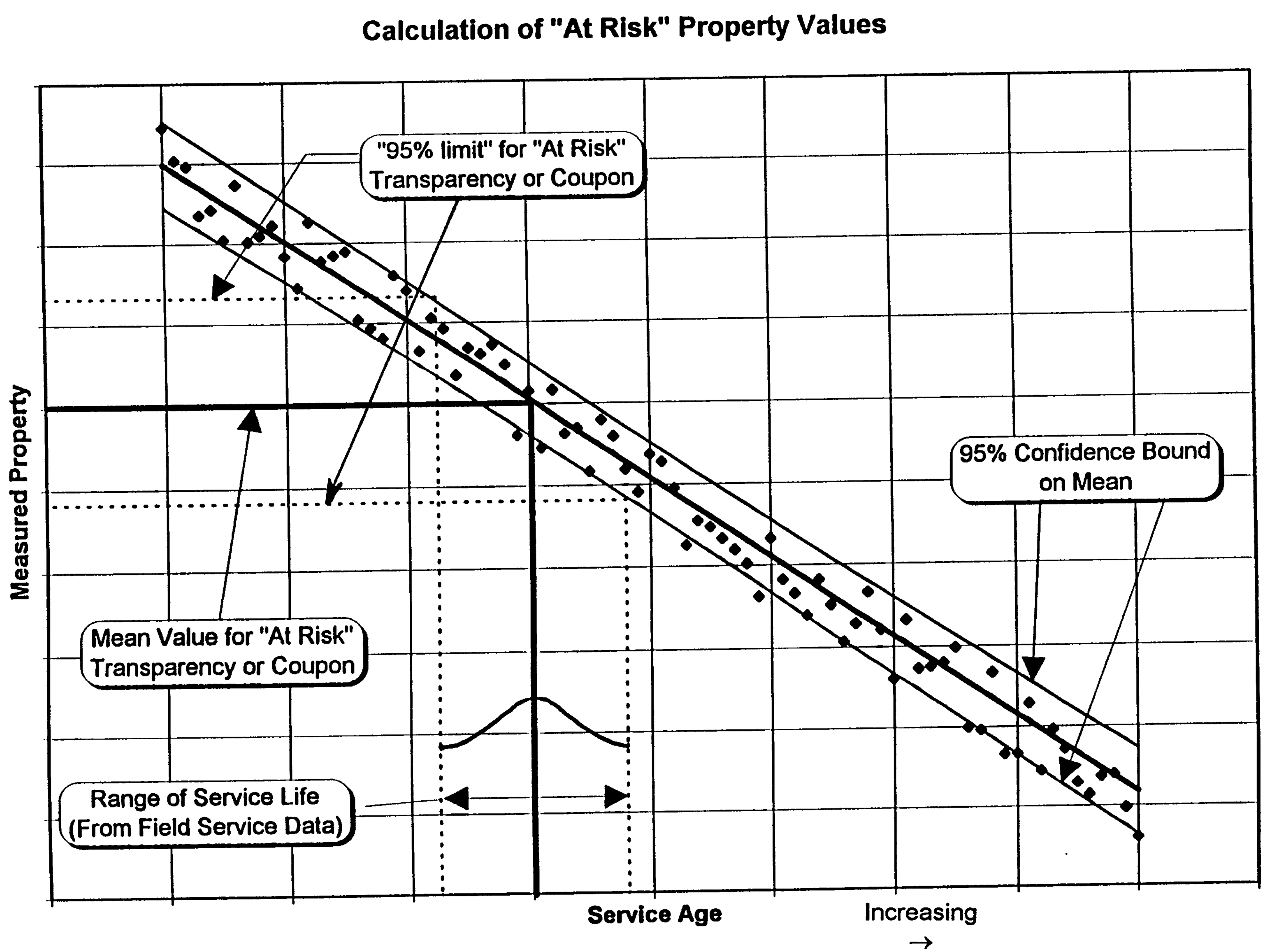


Figure 2. Hypothetical Degradation of Coupon Scale Test Properties with In-Service Aging.

Evaluation of Artificial Conditioning Time

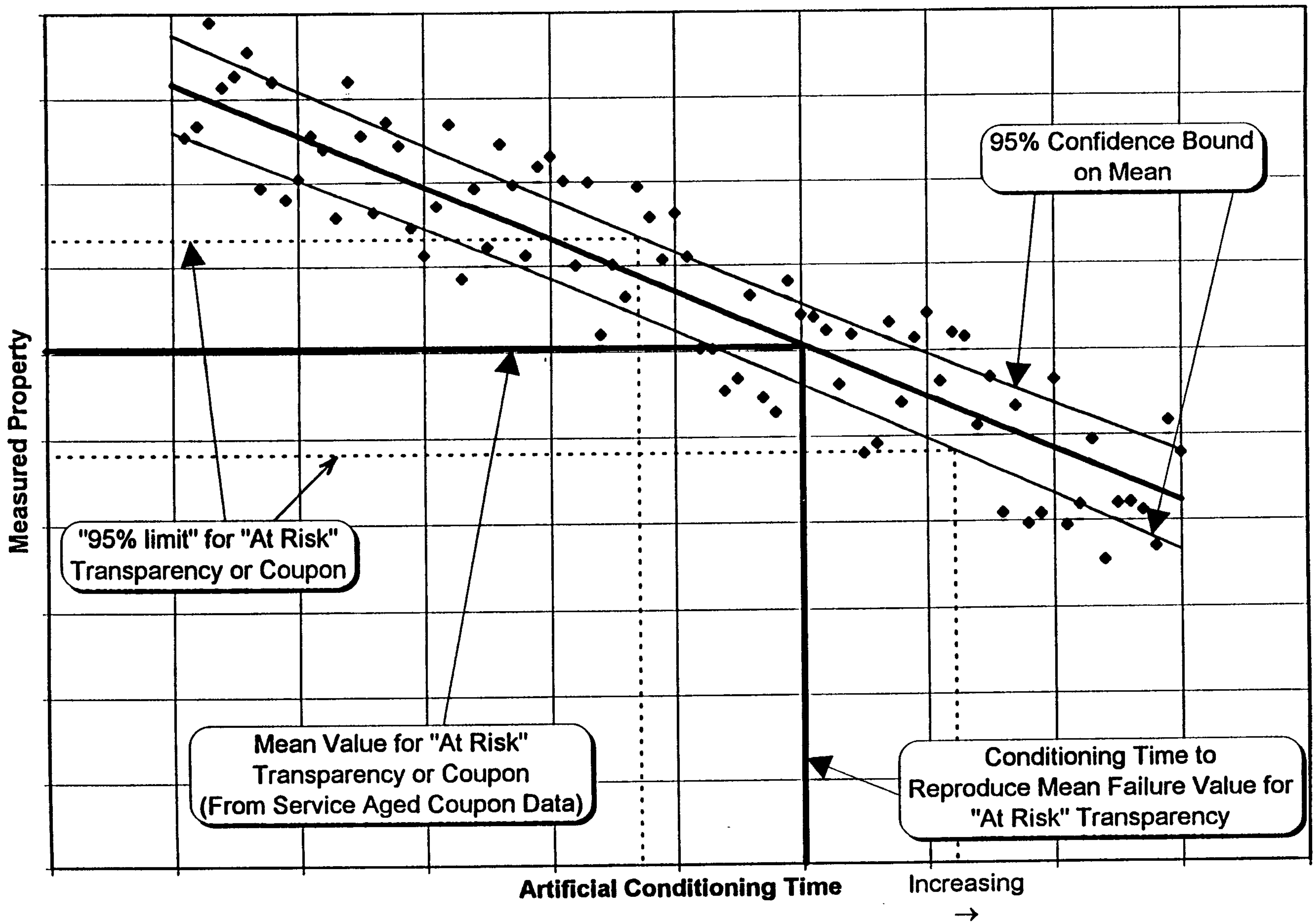


Figure 3. Hypothetical Degradation of Coupon Scale Test Properties with Artificial Aging.

general meteorological conditions, which can be obtained from “base-at-removal” data. It must be assumed that coupons from one or two transparencies with the same service age and base-at-removal will be representative of all transparencies with the same service age and base-at-removal. The assumption would be invalid in a case where 3 years of service life on one airplane might be much more severe (in terms of flightline and in-flight thermal and pressure profiles) than 5 years of service life on another airplane (because of variations in missions that might be flown).

In addition to scatter caused by in-service aging, it is expected that there is scatter or variability among new (baseline) transparencies, which could be caused by manufacturing process variables, lot-to-lot material variability, and other factors. While one can measure certain properties for baseline (new) transparencies and for service-aged transparencies, one does not know <u>baseline</u> values for the service aged transparencies. An average value and a confidence interval can be assumed based on testing of baseline transparencies. However, the scatter which exists might be large and interpretations based on test results of service-aged transparencies must be cautious.

For example, a certain measured property for a failed transparency with 1 year of service life might be extremely low compared to average values for that property in baseline transparencies. However, that property might have initially been very low for that transparency (if it would have been measured when the transparency was new) which would explain the short service life. The transparency may also have been exposed to exceptionally severe or unusual peaks in environmental or meteorological factors which would contribute to a short service life. Scatter in the service aged degradation curves may make it difficult to establish a trend similar to that of artificially aged degradation curves. In a like manner, field data may also indicate that "failure times" or "service lives" for a particular failure mode contain so much scatter that it may be difficult to find or establish a "failure value" for an identified property (or combination of properties).

3.2. Review of Phase I and Phase II Coupon Test Results

As discussed in the Phase II Test Plan [8], the F-111 windshield was chosen in Phases I and II to develop and demonstrate a coupon-scale test methodology. Test methods chosen for evaluating these transparencies were limited to those which were established or required minimal development and which addressed common failure modes for these types of

transparencies. Abrasion, aging, crazing, cracking, and delamination were chosen as the failure modes to be investigated. Artificially aged coupons were tested in Phase I. Results can be summarized by the following: abrasion and crazing failure modes were reproduced by artificial aging; delamination mechanisms were nominally reproduced by artificial techniques (although full scale effects were not duplicated at the coupon level); edge cracking and acrylic aging were not reproduced by the artificial technique. Additional tests to identify acrylic aging were also conducted. Microhardness tests showed changes due to artificial aging to be significant. Density changes were also noted, but only for one manufacturer [2].

Service-aged coupons were tested in Phase II. Phase II test data indicated a high degree of scatter for property values as a function of service age. For some properties, the values at failure from service aged coupons encompass the entire range from maximum to minimum value measured for artificially aged coupons. For example, Figure 4 shows baseline Haze (no abrasion cycles) values for service aged windshields from both manufacturers. Haze values span the range from 3-10 percent for the failure modes associated with haze measurement (modes 1, 5, 6, 12). Ignoring modes 1 and 12 (craze), the range is reduced to 3-8 percent. Figures 5 and 6 show the results of Phase I abrasion tests combined with artificial weathering. For PPG specimens, the range of haze values from 3-8 percent includes data points along the entire range of artificial weathering time (which represents the assumed range of haze values for service-aged windshields). For Sierracin, the 3-8 percent haze band corresponds with an artificial weathering range of 2 weeks QUV exposure through 8 weeks QUV with 200 cycles of abrasion. The spread in the data, along with an absence of baseline in-service data (so that <u>increases</u> in haze could be measured and correlated) has prevented a meaningful correlation between test results from service and artificially aged coupons.

Craze data also show scatter which makes correlation of test results from service aged and artificially aged coupons very difficult. Figure 7 shows stress craze test results (using isopropyl alcohol) from service aged transparencies. The minimum craze stress in windshields that failed by crazing (modes 1,12) is indeed generally lower than minimum craze stress which failed by other modes. The range of "failure values" is fairly narrow: 1500 to 2250 psi. However, when this range is applied to artificially weathered samples (Figure 8), the range of corresponding artificial weather times goes from 0 to 8 weeks (across the entire test range). In fact, most of the artificially aged PPG specimens started out with baseline craze values below 1500 psi. As in the haze tests, the service aged test results suffer from the lack

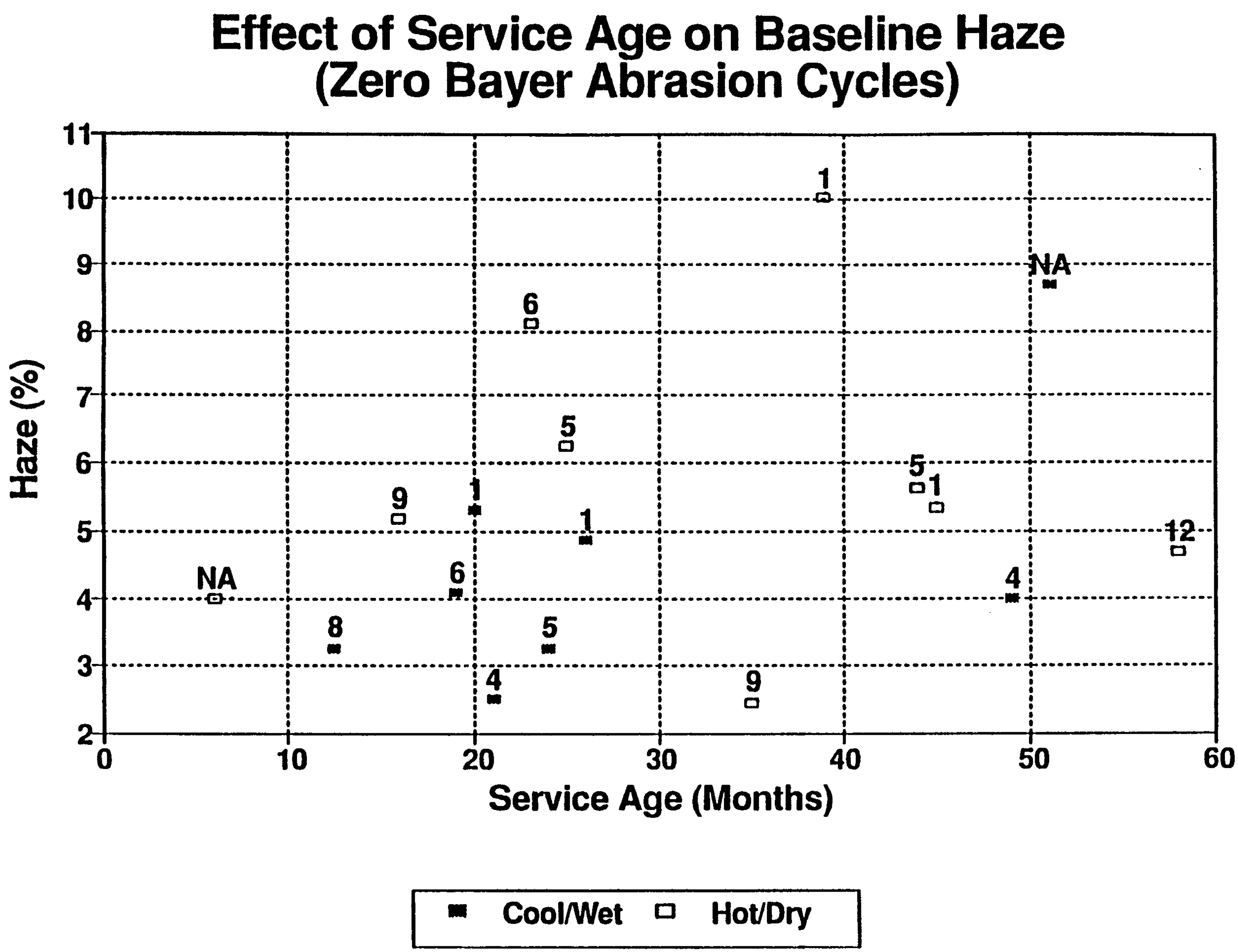


Figure 4. Baseline Service Aged Haze Values.

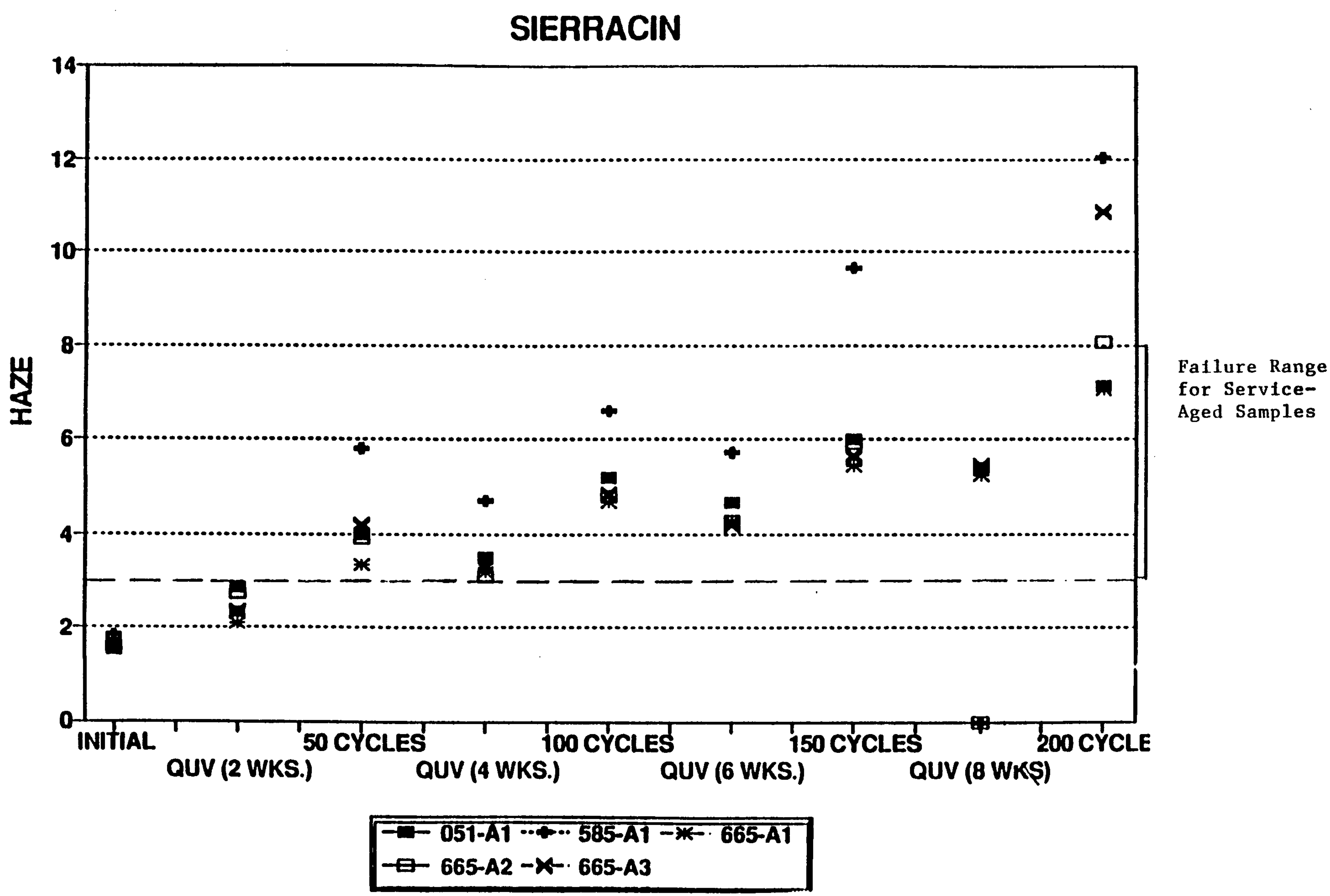


Figure 5. The Effect of Combined QUV Weathering and Oscillating Sand Abrasion for Sierracin Specimens.

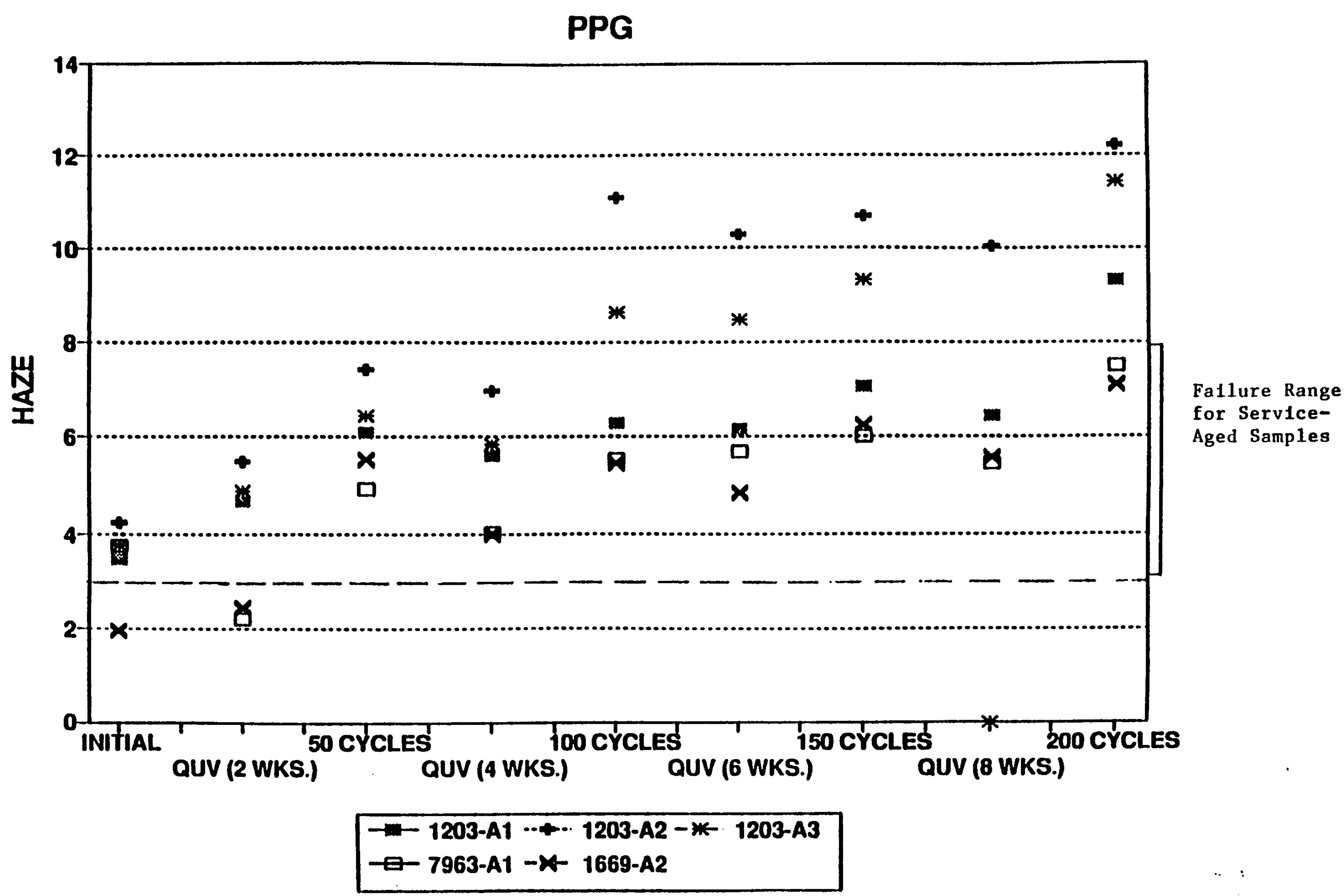


Figure 6. The Effect of Combined QUV Weathering and Oscillating Sand Abrasion for PPG Specimens.

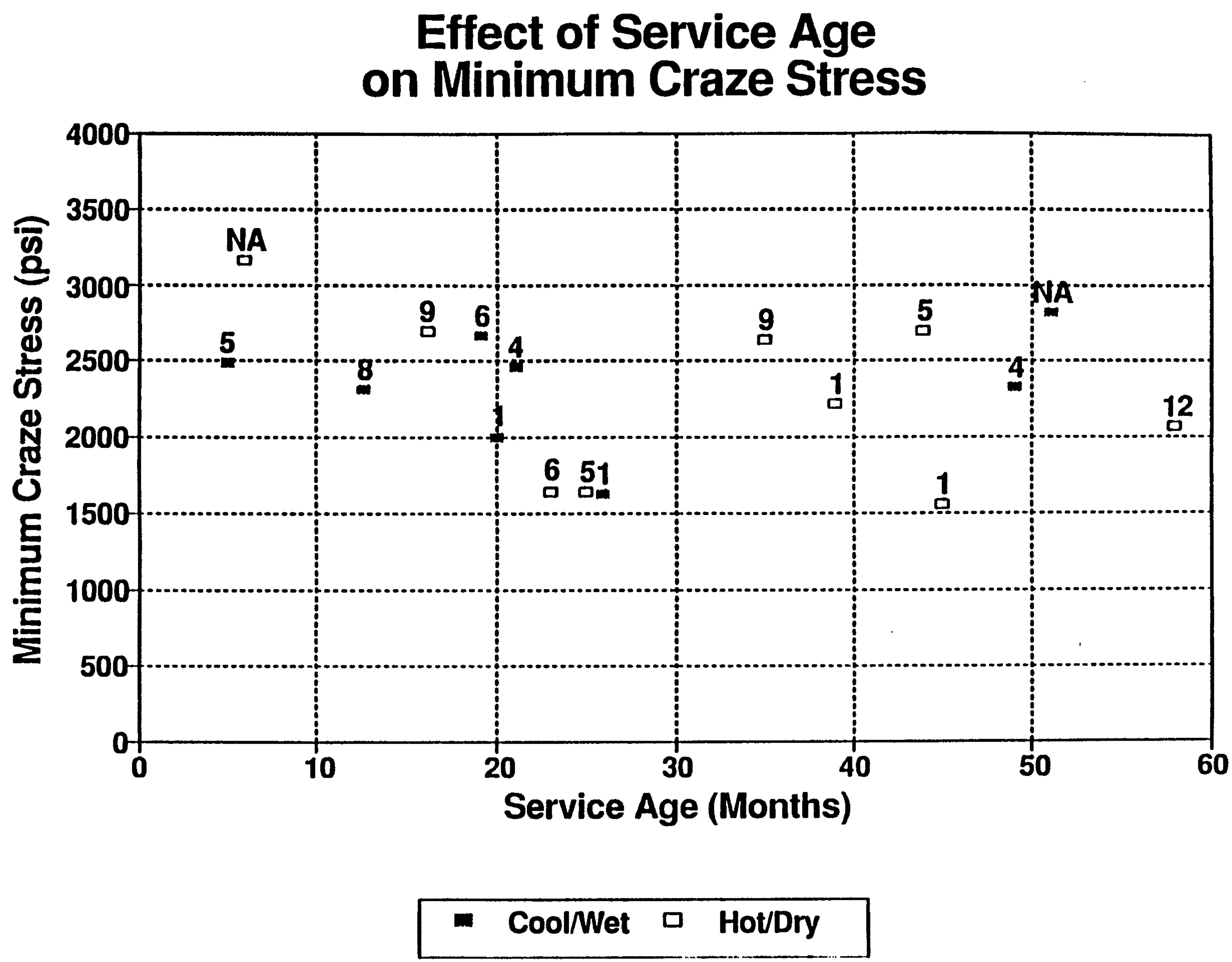


Figure 7. Minimum Craze Stress of Service Aged Coupons.

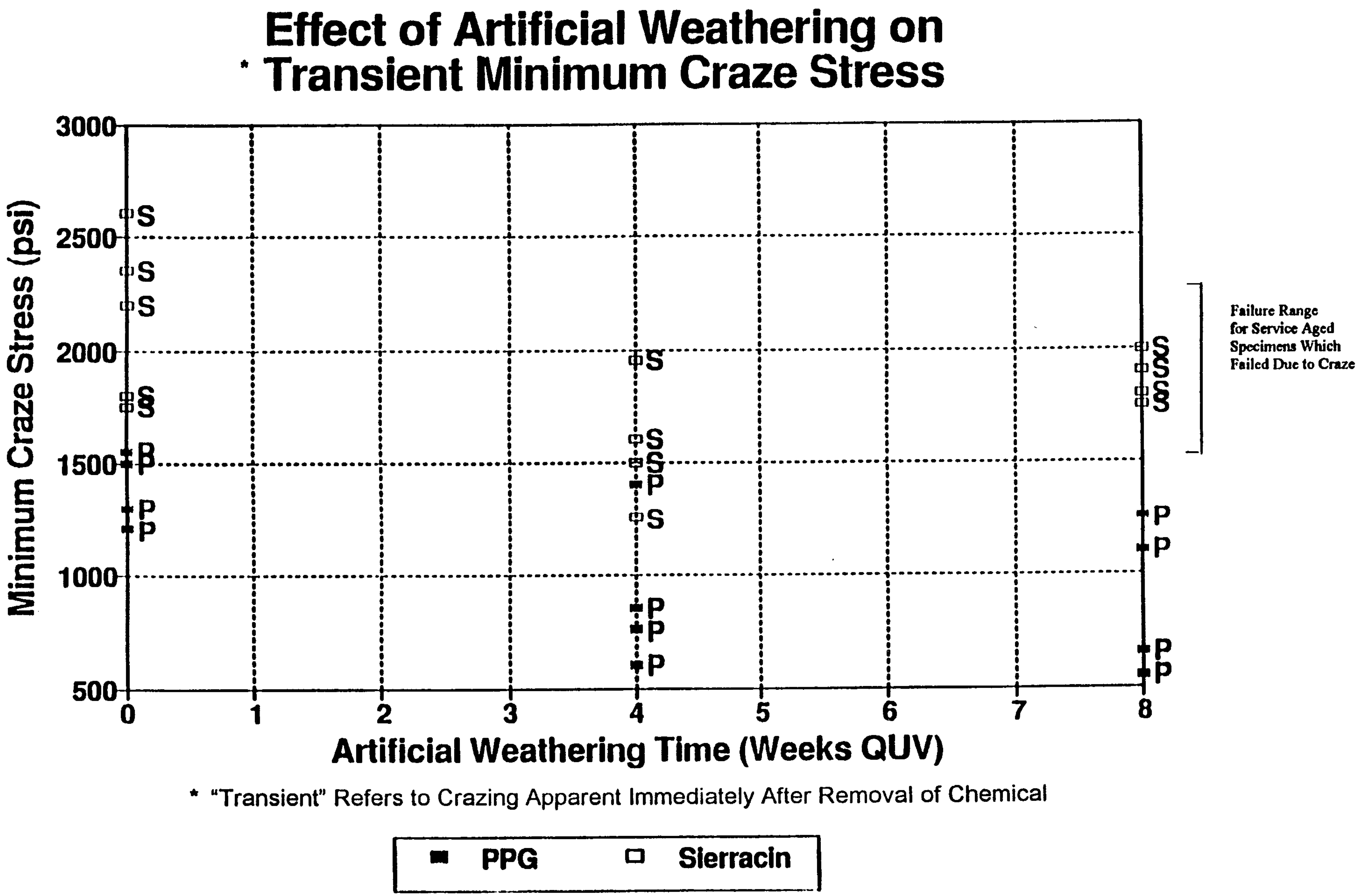


Figure 8. Minimum Craze Stress of Artificially Aged Coupons.

of baseline data, which would allow changes in craze resistance to be evaluated. Note that most of the baseline measurements (0 weeks QUV) in Phase I indicate minimum craze stresses within or below the craze stress "failure value" (1500-2250 psi) indicated by Phase II test results.

The conclusions from the Phase I and Phase II tests indicate that the following improvements must be made to the durability test methodology before the methodology can be used to accurately predict service life:

1) Better artificial weathering and environmental simulation techniques must be developed. Phase I results showed that simulated weathering did not reproduce all of the failure modes that have been shown to exist through field service data. Low moisture acrylic can be placed in a QUV machine and exposed to 10 years worth of UV, temperature, and moisture cycling without significant degradation. The same acrylic in the field may craze in 6 months [9]. It is clear that other factors must be taken into account when simulating the service environment.

2) Better knowledge and understanding of in-service conditions (environmental, operational, etc.) must be obtained in order to accurately simulate conditions in a coupon-scale test. At this point in time, only very rough approximations of environmental conditions can be assumed for any given transparency. Approximations are based on weather data from the base at which the transparency was removed from the aircraft. During its service life, the transparency may have been exposed to numerous and various environments as the aircraft was flown from location to location. No method exists to track the actual exposure of the transparency to radiation, temperature, moisture, or airborne pollutants which may affect durability. Until techniques are developed to adequately measure environmental conditions, artificial weathering techniques which accurately simulate exposure conditions will be difficult to develop.

Non destructive test methods must be developed which can be used in an on-going basis in the field. The test methods now used are almost exclusively destructive in nature, meaning a test can be applied only once during a transparency's lifetime: at the beginning, which renders the transparency unusable, or at the end of its service-life, meaning no baseline data are available. The use of destructive techniques mandates that changes in properties for groups of transparencies be calculated. Data for new transparencies must be pooled, and

data for transparencies with any given service life must be pooled. The result is considerable scatter in the data, making trend identification extremely difficult. Non destructive methods would allow changes in properties for an individual transparency to be tracked over the life of the transparency.

3.3. Test Matrix for Phase III

With the Phase I and Phase II results in mind, discussions between UDRI and WL/FIVE-1 personnel led to the decision that the Phase III coupon test program would concentrate on the following items:

1) Investigation of one failure mode, rather than all modes which have been noted in field data. Since crazing of the outer acrylic ply has been noted as a frequently occurring failure mode, and significant previous work has been done in the area of crazing, acrylic crazing was selected as the focus for Phase III.

2) Identification of test methods which show definite trends in properties for service-aged transparencies. Test methods which were conducted on service-aged F-16 transparencies include X-ray Photoelectron Spectroscopy (XPS) and Fourier Transform Infrared Spectroscopy (FTIR). Craze testing was also conducted on service-aged F-16 transparencies. Although craze testing did not produce clear trends with service life in Phase II testing, the Phase III samples were of improved quality and it was thought that they might show trends not evident in Phase II (due to improved handling methods after removal from service).

3) Investigation of alternative simulated exposure techniques that may be related to the selected failure mode. Inspections of transparencies removed from the field have revealed crazes emanating from the remains of insects which have impacted the transparency [9]. Recent water impact studies of acrylic have revealed microscopic damage which is not visible to the naked eye, and may reduce craze resistance [10, 11]. From these examples, it is clear that QUV exposure is not sufficient to simulate all of the environmental effects which may cause crazing. To explore the effect of solid and liquid impact with craze resistance, exposure to simulated rain and sand exposure were conducted on acrylic sheet craze beams prior to craze testing.

3.3.1. Service Aged Coupon Tests

The front left quarter of thirty-five service aged F-16 canopies were obtained from Texstar, Inc. The canopies were rejected for refurbishment as part of Texstar's F-16 Strip and Recoat program, and were flagged for disposal. Table 1 lists details of the canopy portions obtained. The outer cast acrylic ply is nominally 0.125 inch thick.

Table 2 shows the matrix of tests conducted on the service-aged parts. As shown in Table 1, the service aged parts can be roughly grouped into four geographic locations. (While grouping according to specific weather parameters was used in the Phase III Field Service Data Analysis, broad geographic grouping was used in some instances in the coupon tests to create larger pools of data.) Given two manufacturers and four geographic groups, a total of eight distinct sets of canopies were defined. Referencing Table 2, surface analyses, consisting of appropriate combinations of Fourier Transform Infrared Spectroscopy (FTIR), Ultraviolet/Visible Transmission (UV/VIS), and X-ray Photoelectron Spectroscopy (XPS), were conducted on a service-aged canopy with long service life plus a baseline (no service life canopy) for a total of 6 tests. Density, the only property to show a discernible trend with canopy age, was repeated three times for all available service-aged canopies, for a total of 105 tests. Hardness, a relatively simple test to conduct, was repeated six times for each canopy, resulting in a total of 210 tests. Craze tests were repeated five times on a short service life and a long service life canopy from each set, for a total of 80 craze tests. The complete matrix included a total of 401 individual tests. Note that the test matrix described here differs slightly from that given in the Coupon Scale Test Plan [5]. Scheduling limitations reduced the number and type of tests originally planned.

3.3.2. Artificially Conditioned Coupon Tests

Table 3 shows the matrix of artificially conditioned coupons tested during Phase III. For Phase III tests, artificial conditioning consisted of exposure to simulated high velocity dust environments and water impact (rain) environments. Simulated exposure coupled with QUV exposure, also called "Combined Effects Testing," was conducted during the Mission Integrated Transparency System (MITS) Program. However, percent haze and visual observation of coating pitting, delamination, and removal were the only metrics by which exposure damage was measured. Craze testing was not conducted after rain erosion testing

Table 1. Service Aged F-16 Canopies to be Used in Phase III Coupon Testing.

S/N	S/R	Mfg Date	Remove Date	Part Life (Months)	Base name	Geo Loc*	Type Code**	Manufacturer name
3042	S	11/91	10/93	23	Luke AFB, AZ	1	CFS	Sierracin/Sylmar Corp.
2976	S	10/91	02/94	28	Hill AFB, UT	1	CFS	Sierracin/Sylmar Corp.
2369	S	06/90	03/94	45	Hill AFB, UT	1	CFS	Sierracin/Sylmar Corp.
1264	S	08/87	02/94	78	Buckley ANGB, CO	1	CFS	Sierracin/Sylmar Corp.
1074	S	04/87	10/93	78	Luke AFB, AZ	1	CFS	Sierracin/Sylmar Corp.
1295	S	08/87	07/94	83	Carswell AFB, TX	2	CFS	Sierracin/Sylmar Corp.
736	S	02/84	04/93	110	Montgomery, AL	2	AFC	Sierracin/Sylmar Corp.
3191	S	02/92	10/93	20	NAS Key West, FL	3	CFS	Sierracin/Sylmar Corp.
2609	S	10/90	09/93	35	NAS Key West, FL	3	CFS	Sierracin/Sylmar Corp.
1514	S	02/88	06/93	64	MacDill AFB, FL	3	CFS	Sierracin/Sylmar Corp.
1086	S	05/87	10/93	77	Eglin AFB, FL	3	CFS	Sierracin/Sylmar Corp.
3038	S	11/91	03/94	28	Des Moines, IA	4	CFS	Sierracin/Sylmar Corp.
2459	S	06/90	05/93	35	Selfridge ANGB, MI	4	CFC	Sierracin/Sylmar Corp.
756	S	10/86	06/94	92	McConnell AFB, KS	4	CFS	Sierracin/Sylmar Corp.
2853	S	04/92	10/93	18	Nellis AFB, NV	1	CFS	Texstar, Inc.
2384	S	08/90	06/92	22	Hill AFB, UT	1	CFC	Texstar, Inc.
2491	S	01/91	12/93	35	Luke AFB, AZ	1	CFS	Texstar, Inc.
2451	S	12/90	11/93	35	Hill AFB, UT	1	CFS	Texstar, Inc.
1275	S	05/87	08/93	75	Luke AFB, AZ	1	CFS	Texstar, Inc.
1071	S	01/87	09/93	80	Nellis AFB, NV	1	CFS	Texstar, Inc.
3083	S	06/93	07/94	13	Moody AFB, GA	2	CFS	Texstar, Inc.
2655	S	10/92	01/94	15	Moody AFB, GA	2	CFS	Texstar, Inc.
2294	S	03/90	08/93	41	Barksdale, LA	2	CFS	Texstar, Inc.
1209	S	04/87	11/93	79	Shaw AFB, SC	2	CFS	Texstar, Inc.
1136	S	2/87	5/94	87	Richmond, VA	2	CFS	Texstar, Inc.
2813	S	02/92	02/94	24	Atlantic City, NJ	3	CFS	Texstar, Inc.
2543	S	03/91	08/93	29	NAS Oceana, VA	3	CFS	Texstar, Inc.
2701	S	10/91	07/94	33	MacDill AFB, FL	3	CFS	Texstar, Inc.
1206	S	04/87	07/94	87	MacDill AFB, FL	3	CFS	Texstar, Inc.
2791	S	01/92	09/93	20	Des Moines, IA	4	CFS	Texstar, Inc.
2864	S	4/92	2/94	22	Des Moines, IA	4	CFS	Texstar, Inc.
2334	S	05/90	06/93	37	Des Moines, IA	4	CFS	Texstar, Inc.
2257	S	02/90	06/93	40	Des Moines, IA	4	CFS	Texstar, Inc.
1461	S	09/87	09/93	72	Sioux City, IA	4	CFS	Texstar, Inc.
1170	S	03/87	10/93	79	Illinois ANG, Capitol, IL	4	CFS	Texstar, Inc.

* Geo Loc: 1) Sunny Dry 2) Sunny Humid 3) Coastal 4) Mid-Continent

** Type Code: Three letter code indicating Model (A or C); Canopy Type (Forward or Aft); Coating (Solar or Clear)

Table 2. Test Matrix for Phase III Service Aged Coupon Tests

Test	Method	Number of Windshields	Replicates	Total Number
Surface Analysis	FTIR	2	1	2
Surface Analysis	XPS	2	1	2
Surface Analysis	UV/VIS	2	1	2
Density	ASTM D-792	35	3	105
Hardness	Vicker's Machine	35	6	210
Craze	ASTM F791 100% Isopropanol	16	5	80
			Total Tests	401

Table 3. Test Matrix for Phase III Artificially Aged Coupon Tests

Test	Number of Exposure Conditions	Samples per Exposure Condition	Total Samples
Dust Erosion	4	4, Conditions A/D 8, Conditions B/C	24
Baseline Craze	1 (No Exposure)	6	6
Rain Erosion	4	3	12
		Total	42

in the MITS program. To focus the Phase III tests on dust and rain erosion effects, QUV conditioning was not conducted as part of this program.

The dust exposure conditions for the Table 3 matrix were formulated by trial and error using 2 inch square acrylic samples. The exposure times were chosen to produce barely visible, mild, and severe haze damage. Specific particle sizes and velocities were chosen based on use in previous testing [12, 13]. Water impact velocities were chosen to represent the range of velocities which the facility can produce. No previous data had been generated on the damage threshold for the particular acrylic formulation being used in the Phase III tests. Four samples for each of conditions A and D and eight samples for each of conditions B and C were exposed for a total of 24 tests. Three samples were exposed to each of 4 water jet impact velocities for a total of 12 tests.

Test results were analyzed by comparing measurements to a number of factors, including geographic location and environmental factors. Results were grouped into geographic locations according to the base at which the aircraft was stationed at the time of canopy removal. No information was available concerning the amount of time a canopy was located at a given location. As in Phase II [2], bases were grouped into four broad categories for preliminary analysis: Sunny and Dry; Sunny and Humid; Coastal; and Mid-Continent. More detailed analysis was conducted based on environmental factors associated with the climate at the base of removal and the service life of the transparency: Total Radiation Exposure; Highest Average Maximum Temperature; Number of Degree Days (a value related to heating requirements of buildings and enclosures); Number of Rainy Days; and Number of Clear Days. Environmental data associated with a particular air base are data for the closest city for which data were available [14]. While these values do not represent the exact environmental exposure of each canopy, they are the best data available.

Table 4 shows the grouping of bases into the four geographic categories. Table 5 shows the environmental exposure data associated with each base.

Artificially conditioned coupons were fabricated from 1/4-inch-flat acrylic sheet which meets ASTM D 4802 - 94, "Standard Specification for Poly(Methyl Methacrylate) Acrylic Plastic Sheet," Category A-1. Category A-1 is Methacrylate sheet typically manufactured by the cell-casting process. This category represents the best optical-quality sheet. It is characterized by the highest long-term design stress and the highest degree of chemical resistance found in methacrylate sheet.

Table 4. Grouping of Bases into Geographic Categories.

Group Number	Designation	Air Force Bases
1	Sunny, Dry	Luke AFB, AZ Hill AFB, UT Buckley ANGB, CO Nellis AFB, NV
2	Sunny, Humid	Carswell AFB, TX Montgomery, AL Moody AFB, GA Barksdale, LA Shaw AFB, SC Richmond, VA
3	Coastal	NAS Key West, FL MacDill AFB, FL Eglin AFB, FL Atlantic City, NJ NAS Oceana, VA
4	Mid-Continent	Des Moines, IA Selfridge ANGB, MI McConnell AFB, KS Sioux City, IA Illinois ANG, Capitol, IL

Table 5. Environmental Exposure Data for Air Force Bases.

Base Name	Geographic Location	Daily Mean Radiation (Langleys)	Highest Maximum Temperature (Monthly Ave, °F)	Yearly Heating Degree Days	Rain Days (<0.01")	Clear Days
Luke AFB, AZ	1	540	105	1698	34	209
Hill AFB, UT	1	399	92	5866	86	136
Buckley ANGB, CO	1	479	87	6132	86	113
Nellis AFB, NV	1	514	105	2425	21	220
Carswell AFB, TX	2	485	96	2272	81	145
Montgomery, AL	2	418	91	2137	111	107
Moody AFB, GA	2	426	91	1808	107	108
Barksdale, LA	2	439	95	2058	94	128
Shaw AFB, SC	2	426	92	2435	110	126
Richmond, VA	2	319	88	3955	116	101
NAS Key West, FL	3	469	90	89	115	109
MacDill AFB, FL	3	456	90	674	115	90
Eglin AFB, FL	3	456	91	1519	114	101
Atlantic City, NJ	3	362	79	4741	122	118
NAS Oceana, VA	3	319	86	3454	117	108
Des Moines, IA	4	370	87	6446	102	101
Selfridge ANGB, MI	4	352	84	6404	133	81
McConnell AFB, KS	4	413	92	4571	82	130
Sioux City, IA	4	334	89	6160	95	116
Illinois ANG, Capitol, I	4	398	87	5693	113	111

3.4. *Phase III Experimental Coupon Tests and Results*

3.4.1. Surface Analyses

3.4.1.1. Test Objective

The objective of these test methods was to identify changes to the surface chemistry of the outer acrylic ply of service aged transparencies. Fourier Transform Infrared Spectroscopy (FTIR), X-ray Photoelectron Spectroscopy (XPS), and UV Transmission (UV/VIS) were used to examine chemical bonds and molecular structure in the first few microns of the surface.

3.4.1.2. Specimen Configuration

Specimen configurations vary according to the technique being used. FTIR and UV/VIS specimens are typically 1-inch-diameter x 0.125-inch nominal thickness. The XPS technique typically uses small "chunks" of material weighing a few grams.

3.4.1.3. Test Method

Test methods vary according to the technique being used. XPS samples were wiped with hexane prior to XPS analysis.

3.4.1.4. Test Data

XPS, FTIR, and UV/VIS were conducted first on samples from the baseline canopy and from SN 736. At 110 months of part-life, SN 736 had been exposed to a service environment longer than any other canopy being tested. If surface analyses detected no difference in the baseline and "oldest" canopies, surface analyses of samples from other canopies would not be worth pursuing.

XPS results are summarized in Table 6. Example XPS traces for the baseline and SN 736 samples are shown in Figures 9 and 10, respectively. FTIR spectra for baseline and SN 736 samples are shown in Figures 11 and 12, respectively. UV/VIS transmission spectra are shown in Figures 13 and 14, respectively.

Table 6. XPS Results Summary.

Approximate Atom % Surface Compositions of Windscreen Samples, as Determined by XPS

Sample		C		O		F	Si
	O-C=O	C-O	C-C=O,C-H,C	-O, O-Si	=O, O-Si	F-C	Si-O
New, 3852-3	12.7	11.9	47.7	16.5	11.3	---	---
Old, 736-1	12.1	9.4	44.1	15.6	15.6	1.6	2.2

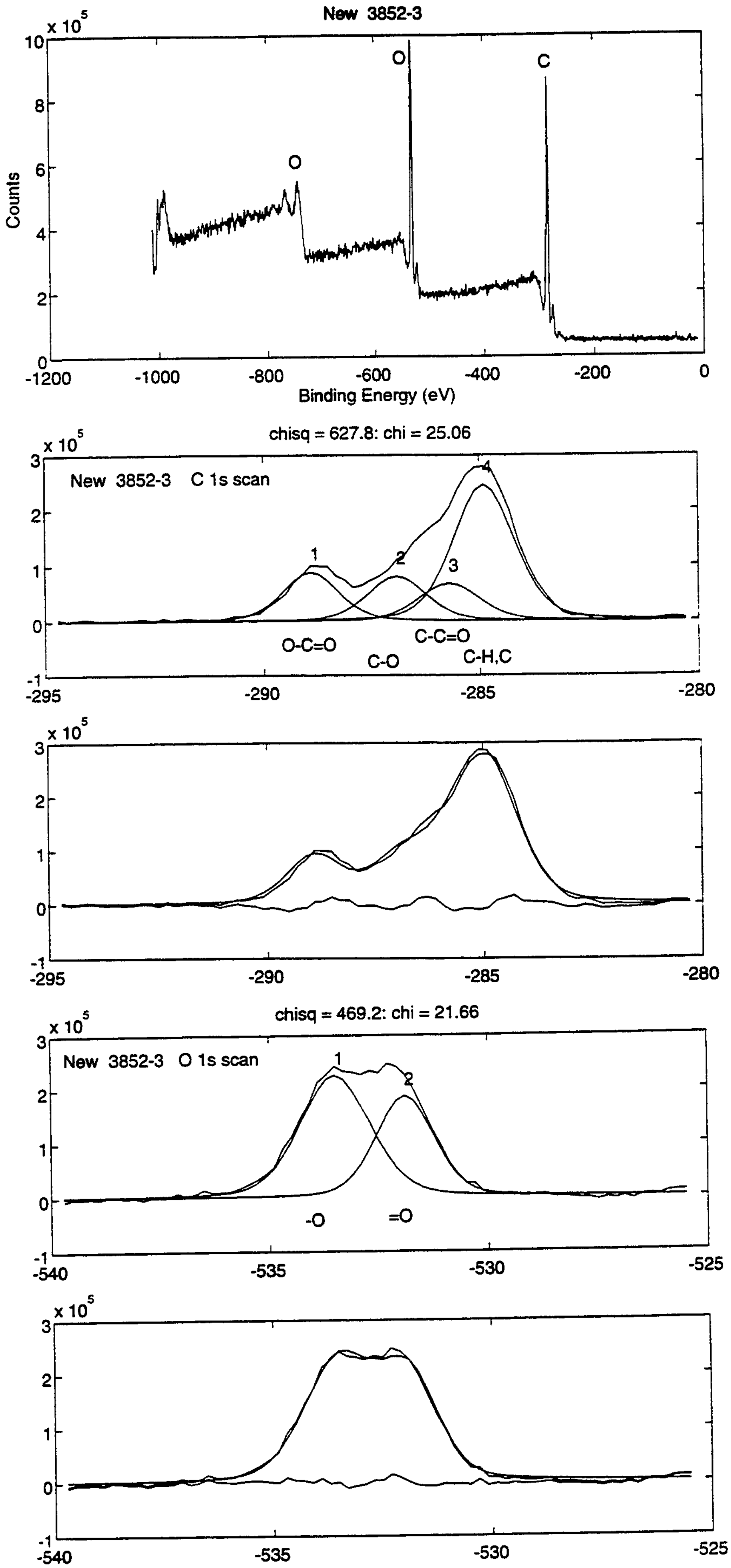


Figure 9. XPS Trace for Baseline Transparency.

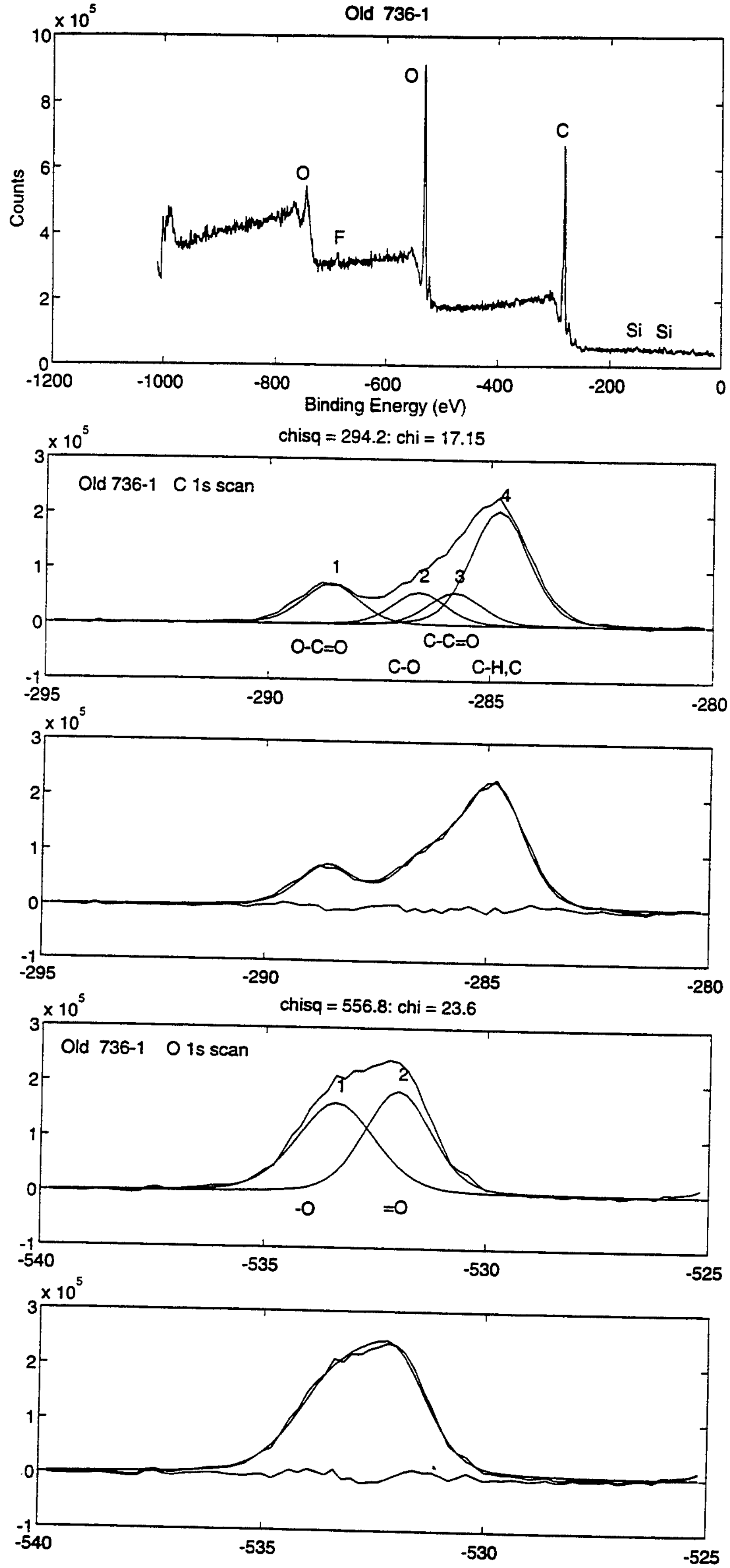


Figure 10. XPS Trace for S/N 736 (Service Life 110 Months).

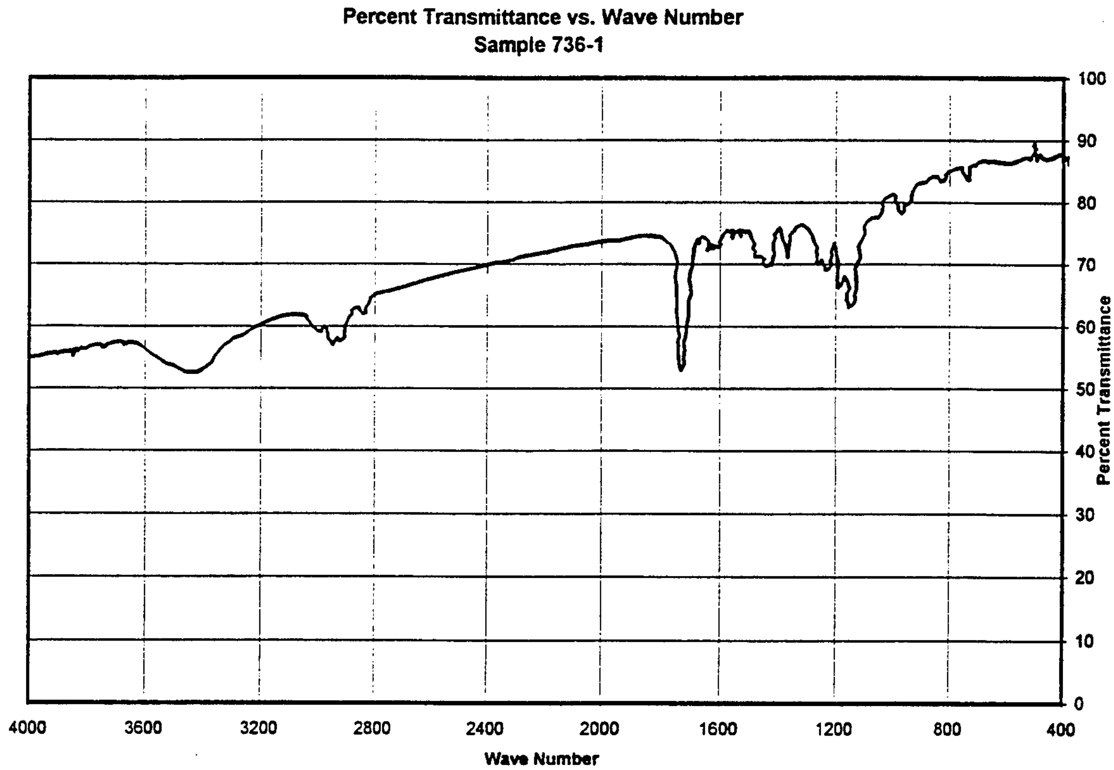


Figure 11. FTIR Spectrum for Baseline Transparency.

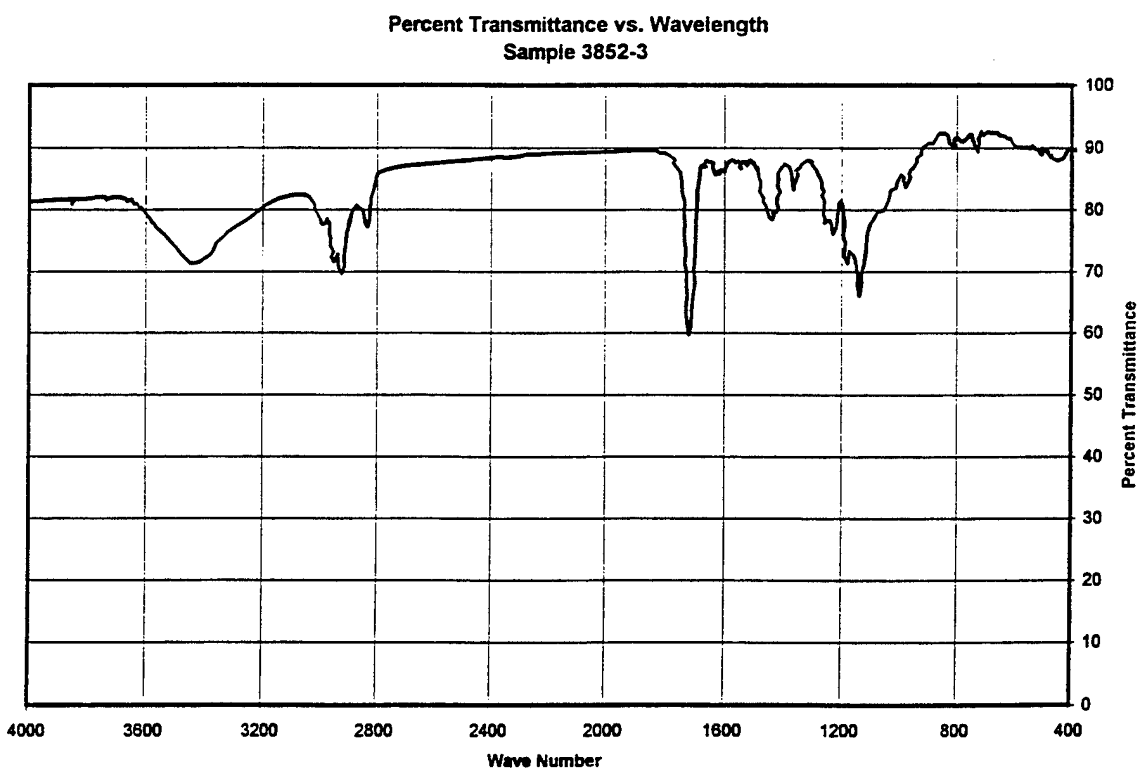


Figure 12. FTIR Spectum for S/N 736 (Service Life 110 Months).

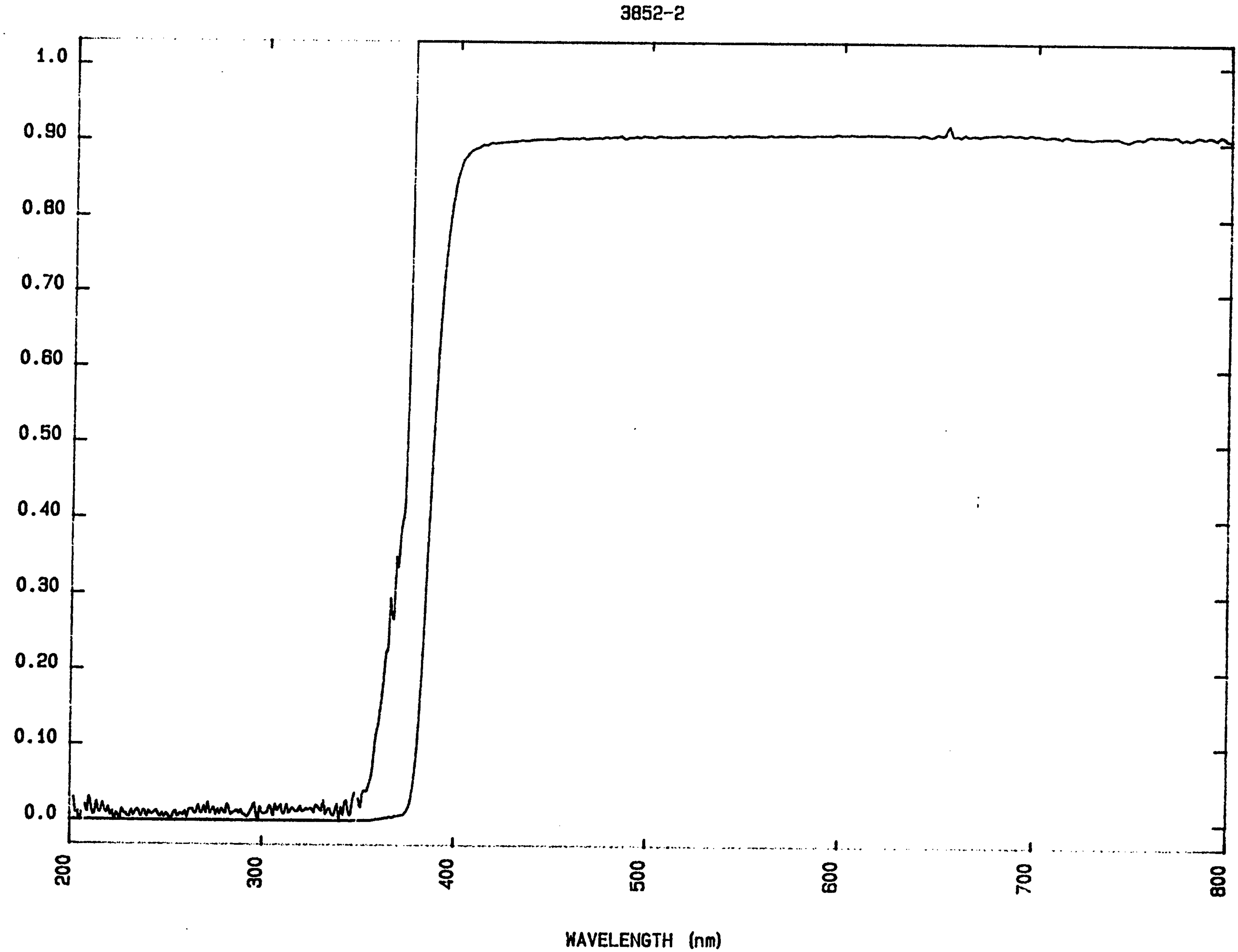


Figure 13. UV/VIS Transmission Spectrum for Baseline Transparency.

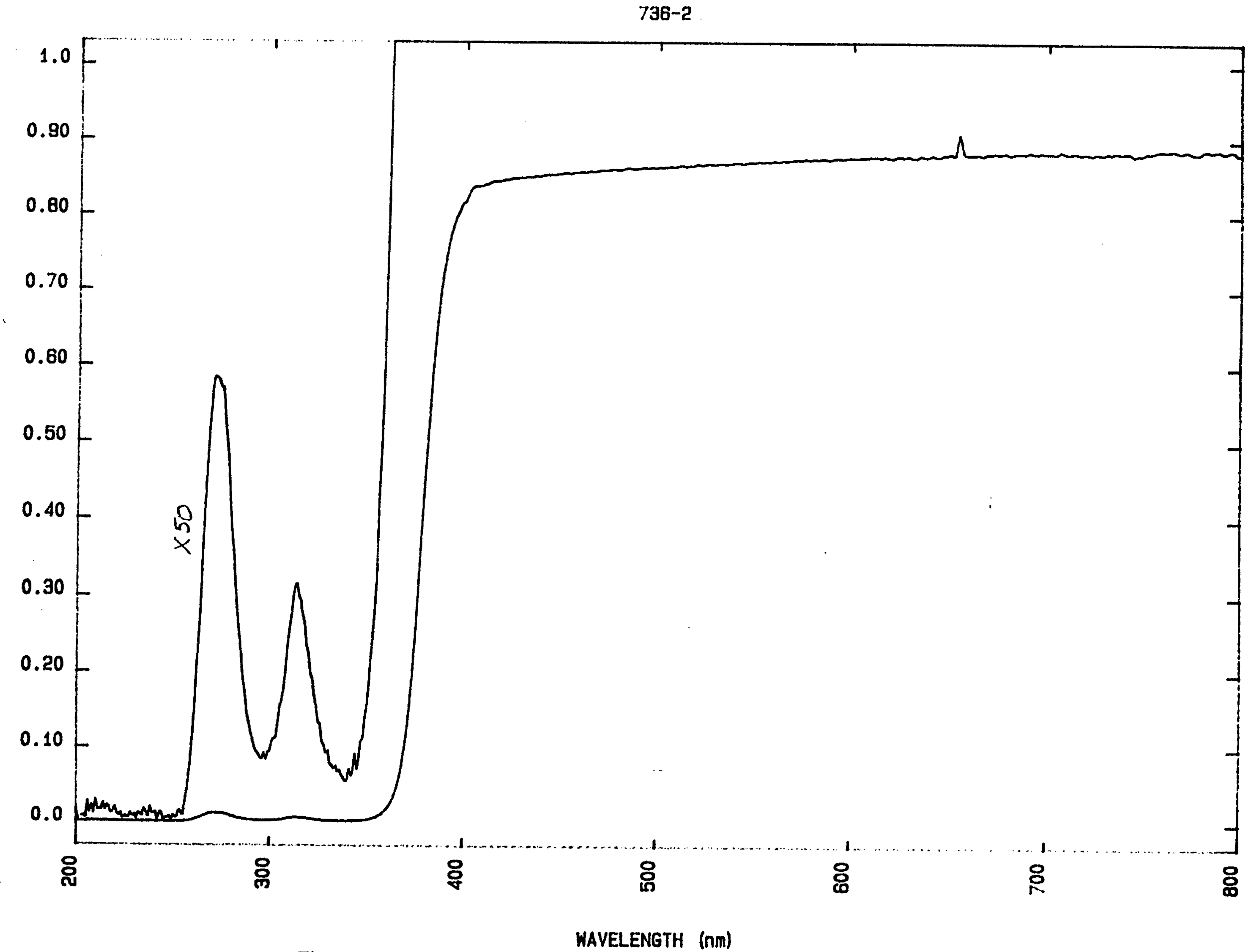


Figure 14. UV/VIS Transmission Spectrum for S/N 736 (Service Life 110 Months)

3.4.1.5. Data Analysis

The XPS survey scan of the new sample shows that carbon and oxygen are the only elements detected. The corresponding carbon 1s shows a strong O-C=O peak; the O 1s scan shows peaks due to -O and =O components with about equal intensity. Results are consistent with an acrylic. The survey scan for the old sample shows that in addition to carbon and oxygen, low levels of fluorine and silicon are detected. The differences are judged to be related to contamination or cleaners. Phase I testing also detected an increase in silicon in coupons which had been artificially weathered, presumably due to surface contamination from the sealant which was used around the edge of the sample to prevent ingress of moisture into the edges of the specimen during QUV conditioning [1]. The acrylic material chemistry of SN 736 is not different than the chemistry of the baseline canopy, indicating no change due to in-service aging.

Differences exist between the baseline and SN 736 samples for both UV transmission and FTIR. Any yellowing caused by aging of the material would cause changes in the onset of UV absorption. However, the differences in the UV spectra appear to be related to different material thickness. Variations in thickness for nominal 0.125 acrylic can be up to +\- 0.010 inch. Thickness differences prevented yellowing-caused changes from being identified. The magnitude of transmission of the baseline FTIR spectrum is noticeably greater than the magnitude of the SN 736 transmission. The difference is attributed to abrasion of the surface. The peaks and valleys of the spectra occur at approximately the same wavenumbers, indicating no chemical differences between the baseline and SN 736 samples.

3.4.2. Density

3.4.2.1. Test Objective

The objective of this test was to determine if in-service aging is affecting the acrylic surface ply. Density decreased as a function of service life and manufacturing date in Phase II testing of service aged F-111 windshields [2]. Density changes are related to aging and embrittlement of acrylic, which influences craze resistance.

3.4.2.2. Specimen Configuration

Specimens were fabricated from the acrylic outer ply material away from the edges in the form of a rectangular bar shape.

3.4.2.3. Test Method

Density was calculated by following ASTM D-792, "Standard Test Method for Density and Specific Gravity of Plastics by Displacement." Essentially, the density was found by the ratio of the weight of the sample in air to the weight of the sample in water. Three density measurements were conducted for each canopy.

3.4.2.4. Test Data

Average acrylic density as a function of service life and date of manufacture are given in Figures 15 and 16. Each data point represents one canopy and is the average of three measurements. Acrylic density as a function of manufacturer and geographic location are given in Figure 17. Each point represents the mean of all density measurements from transparencies associated with the specific manufacturer and geographic location. Top and bottom bars represent the 2σ (standard deviation) limits from the mean. Figures 18 through 22 show acrylic density as a function of Total Radiation, Maximum Temperature, Total Degree Days, Number of Rainy Days, and Number of Clear days.

3.4.2.5. Data Analysis

Figures 15 and 16 indicate no discernible relationship between density and either service life or date of manufacture. Figure 17 also indicates no relationship between density and either manufacturer or geographic location when the data are pooled according to the categorization shown in Table 4. The large variation in the data (represented by the large error bars) is due primarily to variations in density between canopies, rather than variations between samples from the same canopy. Figure 23 demonstrates that 21 out of the 35 canopies tested had essentially no density variations among the three samples tested from each canopy. Figure 23 demonstrates clearly the need for baseline data from each canopy if <u>changes</u> associated with aging are to be identified.

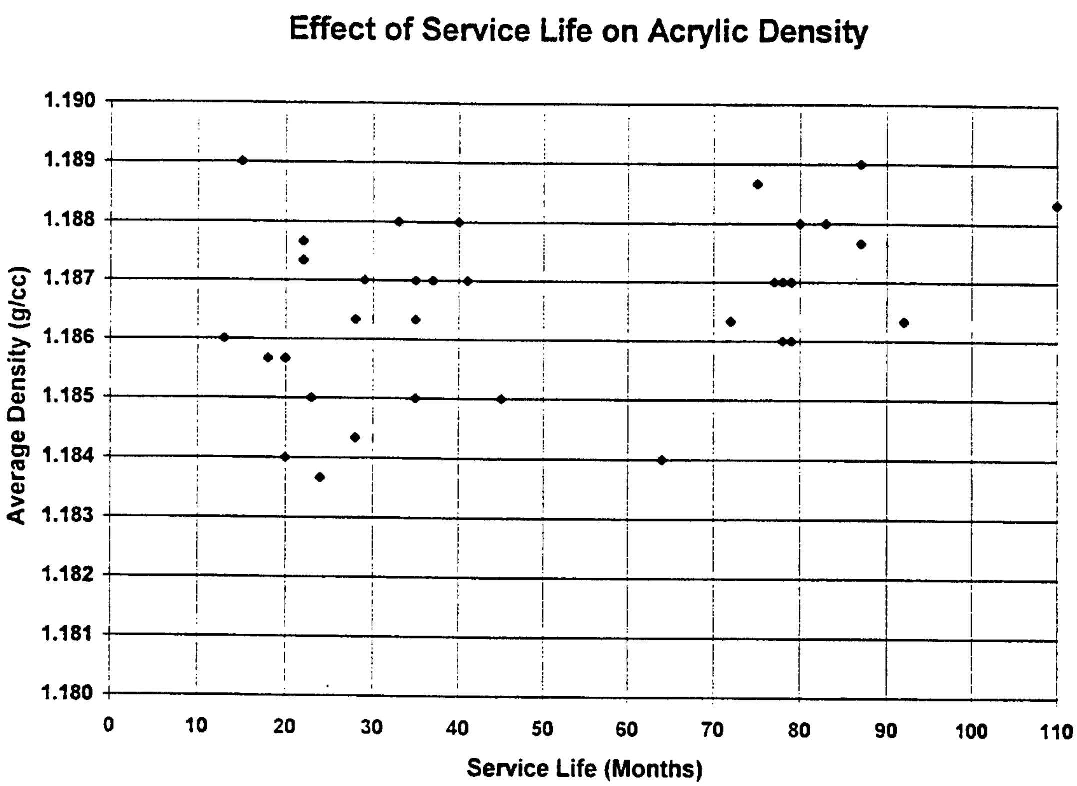


Figure 15. Service Life Effects on Acrylic Density.

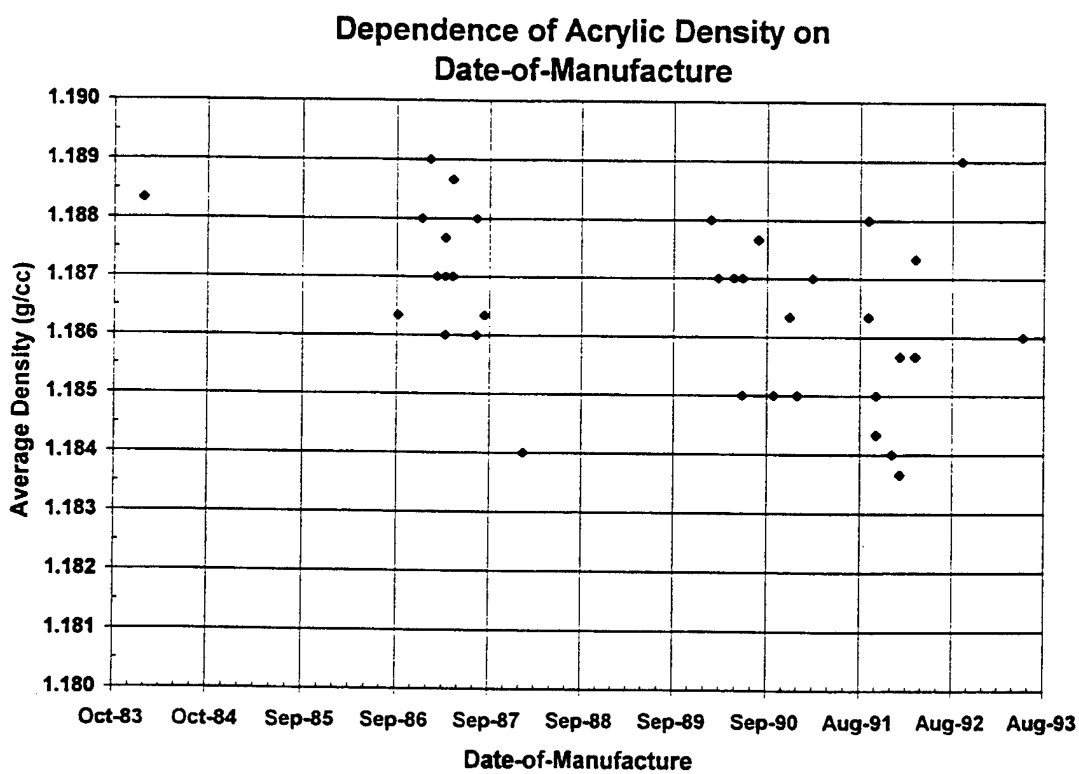


Figure 16. Date of Manufacture Effects on Acrylic Density.

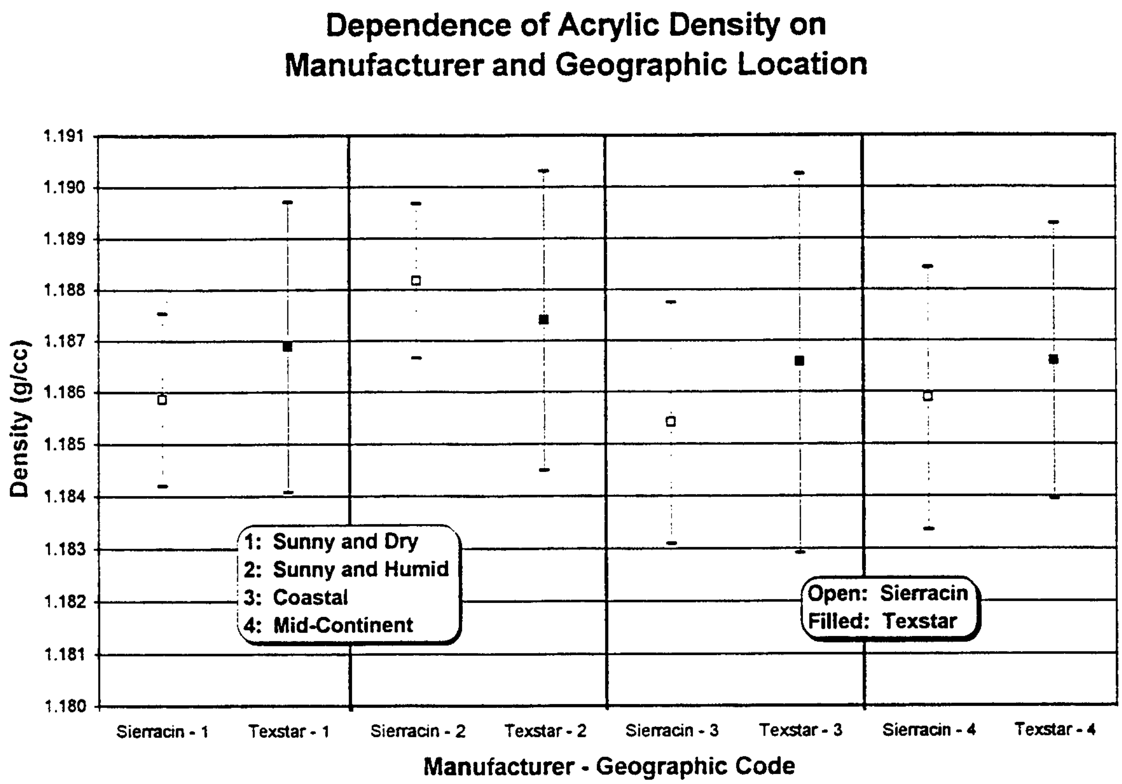


Figure 17. Manufacturer and Location Effects on Acrylic Density.

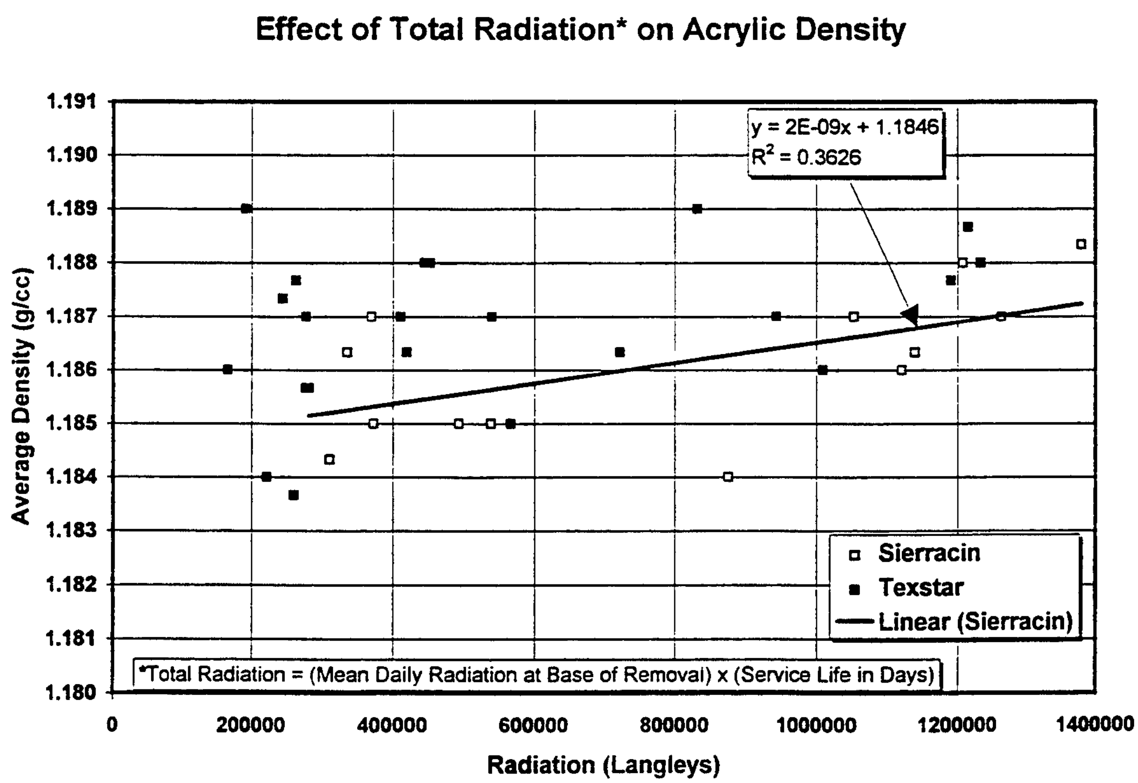


Figure 18. Total Radiation Effects on Acrylic Density.

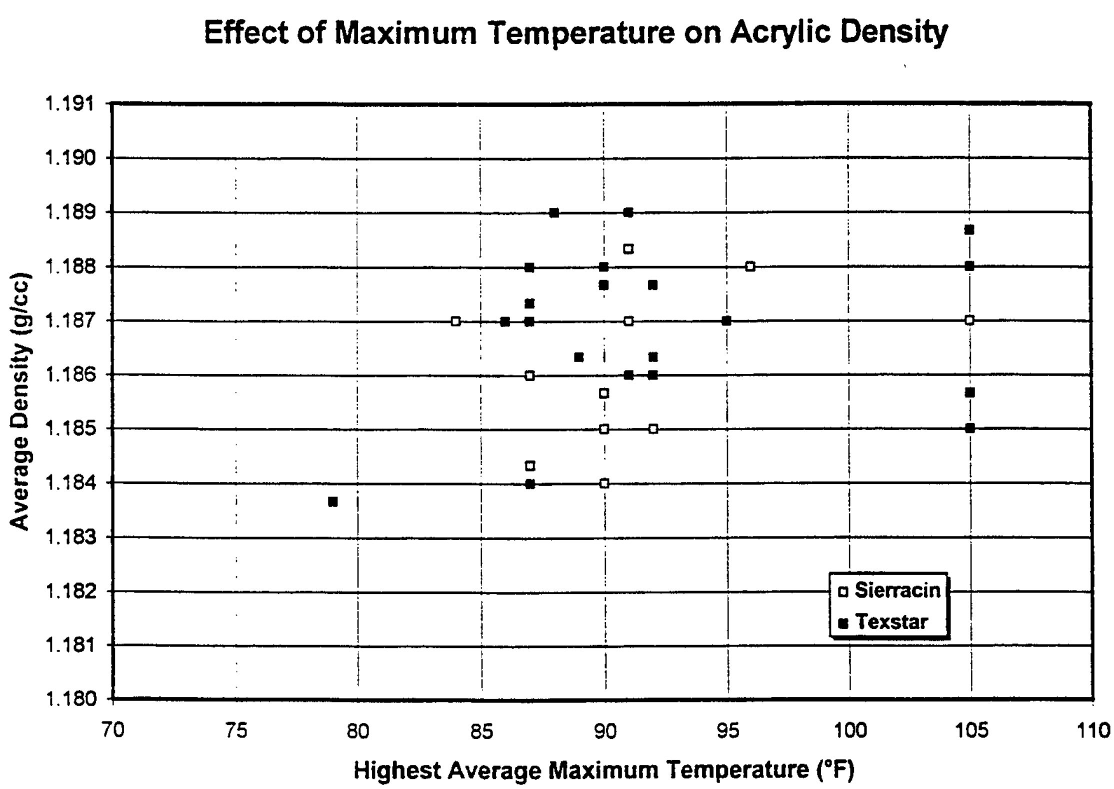


Figure 19. Maximum Temperature Effects on Acrylic Density.

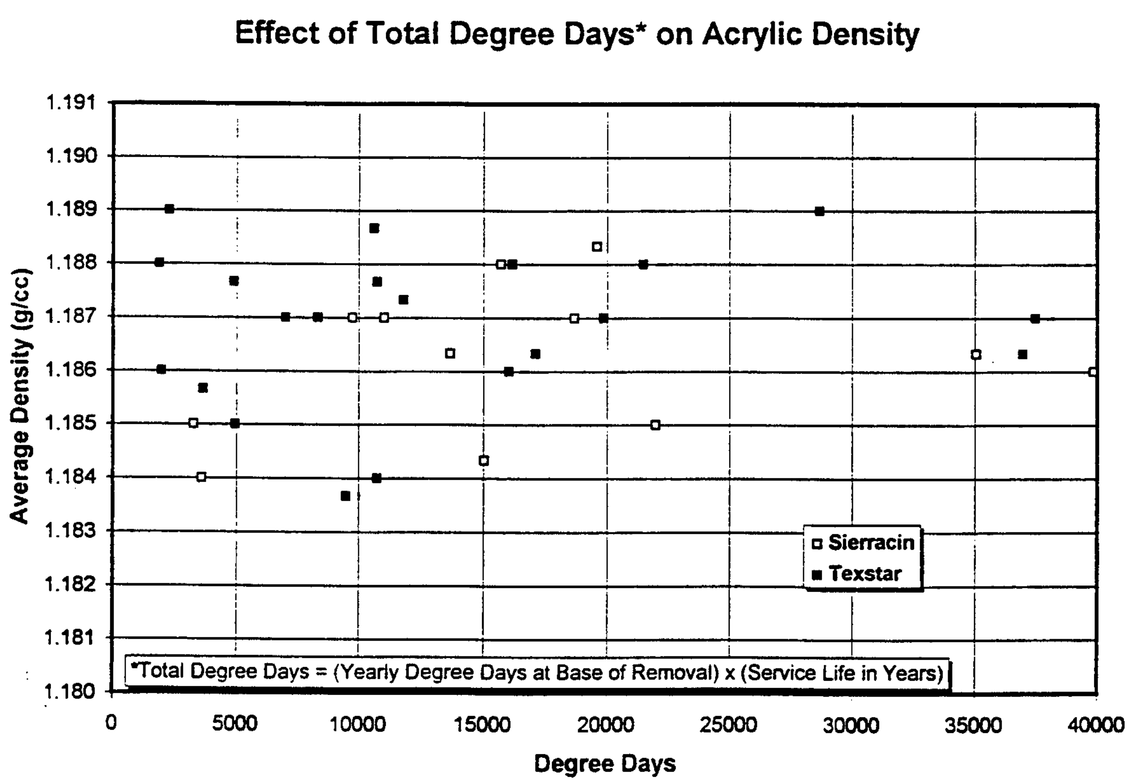


Figure 20. Total Degree Day Effects on Acrylic Density.

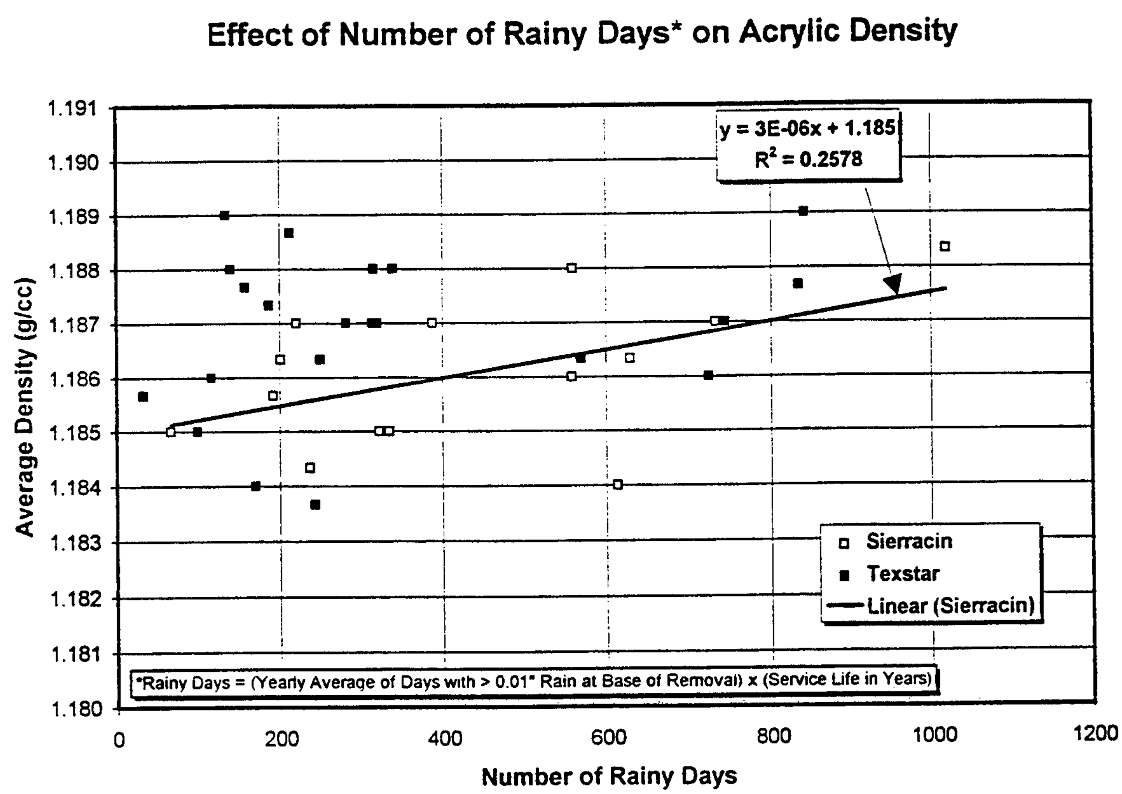


Figure 21. Rainy Day Effects on Acrylic Density.

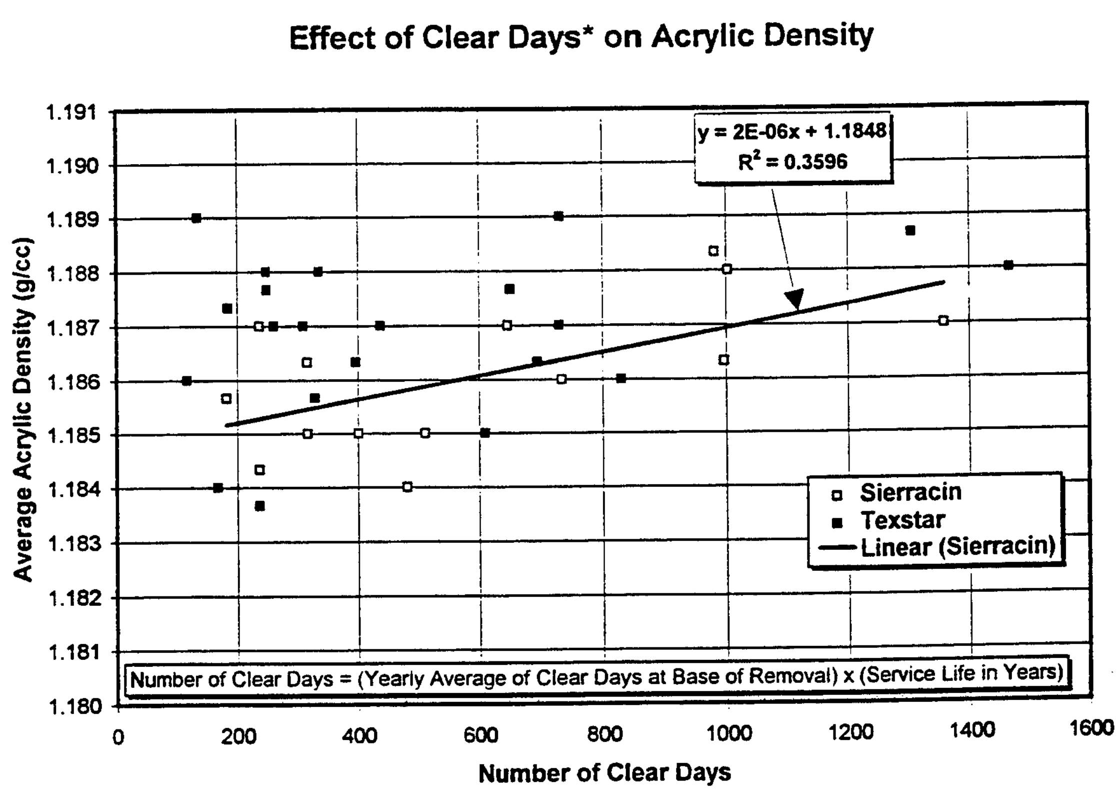


Figure 22. Clear Day Effects on Acrylic Density.

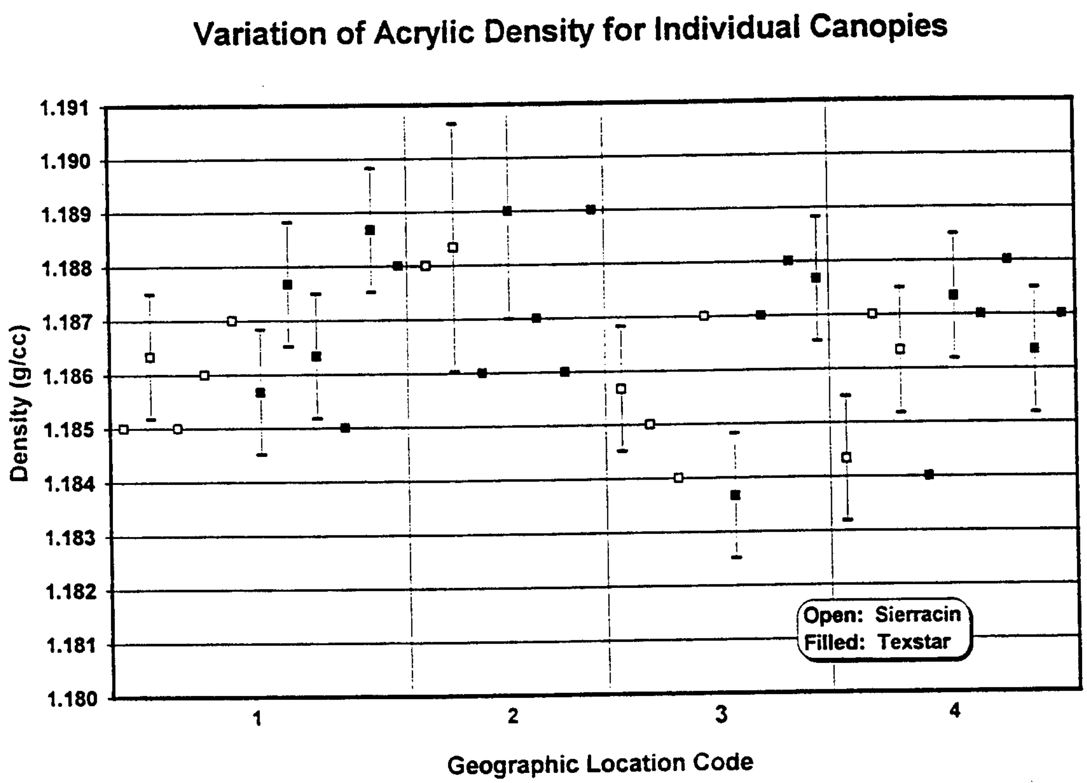


Figure 23. Variations in Acrylic Density Among Individual Canopies.

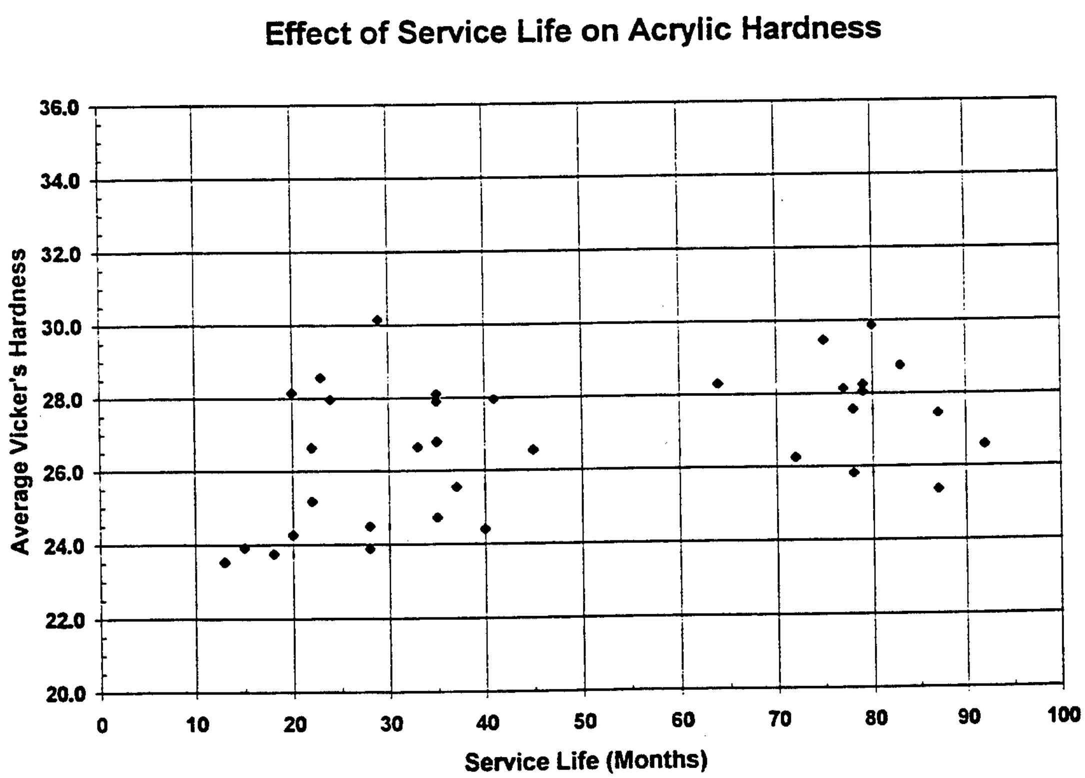


Figure 24. Service Life Effects on Acrylic Hardness.

Figures 18 through 22 show only very mild correlation between acrylic density of Sierracin coupons and Total Radiation, Clear Days, and Rainy Days. Texstar coupons show no correlation for any of the environmental factors. Increase in density is consistent with increased UV exposure and increasing number of clear days. However, the value of R^2 for the best fits is very low. For engineering purposes, $R^2 > 0.9$ is usually required for confidence that the fit represents the data.

3.4.3. Microhardness

3.4.3.1. Test Objective

The objective of this test is to evaluate changes in the acrylic outer ply caused by aging. Microhardness is a relatively simple test to conduct and provides an indication, through changes in mechanical hardness, of aging or chemical modification of the acrylic surface. Microhardness is a more surface sensitive measurement than density (which is a bulk property) and may show different results than density. Phase II test results indicated definite changes in hardness with artificial (QUV) weathering.

3.4.3.2. Specimen Configuration

Two specimens measuring 1 x 1 inch were removed from each canopy. Three hardness measurements were taken on the acrylic outer ply of each specimen. The acrylic outer layer was not removed from the specimen prior to hardness testing.

3.4.3.3. Test Method

Measurements were made using a Vicker's Hardness test machine, consisting of a diamond tipped indentor and a 200-gram loading mass. Results of the test are in the form of indentor penetration distance into the material surface. The distance is converted into a Vicker's hardness number. Three indentations were made on each specimen, for a total of six hardness measurements per canopy.

3.4.3.4. Test Data

Average acrylic hardness as a function of service life and date of manufacture are given in Figures 24-25. Each data point represents one canopy and is the average of three

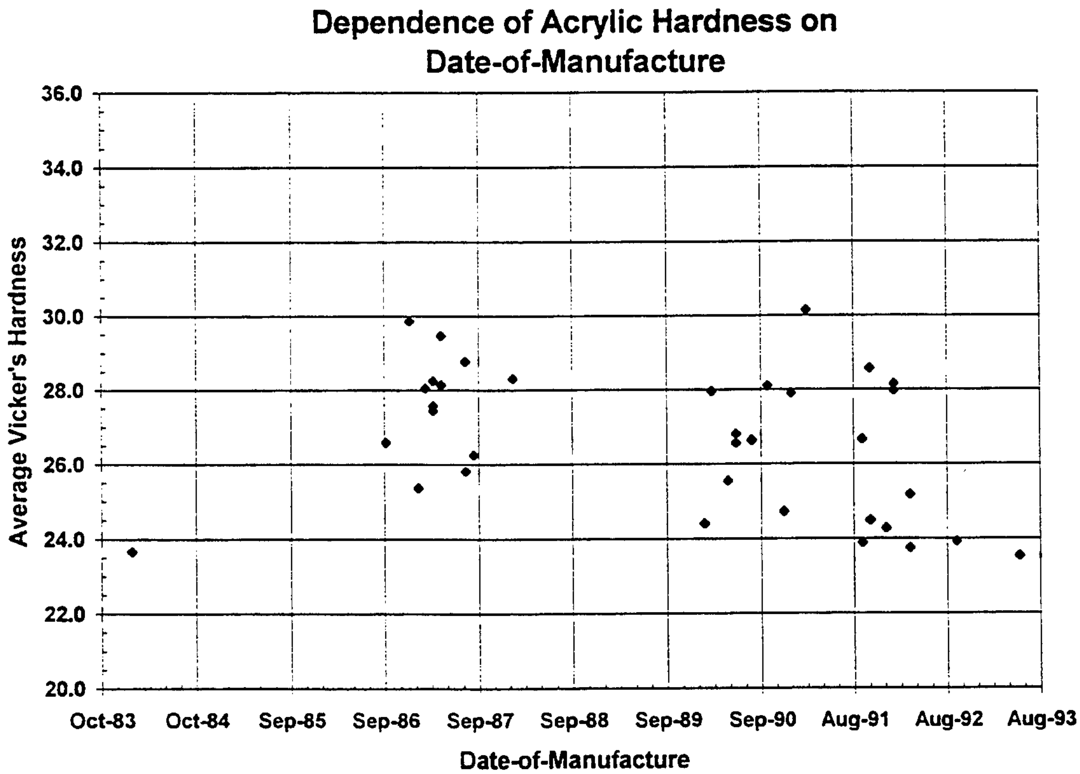


Figure 25. Date of Manufacture Effects on Acrylic Hardness.

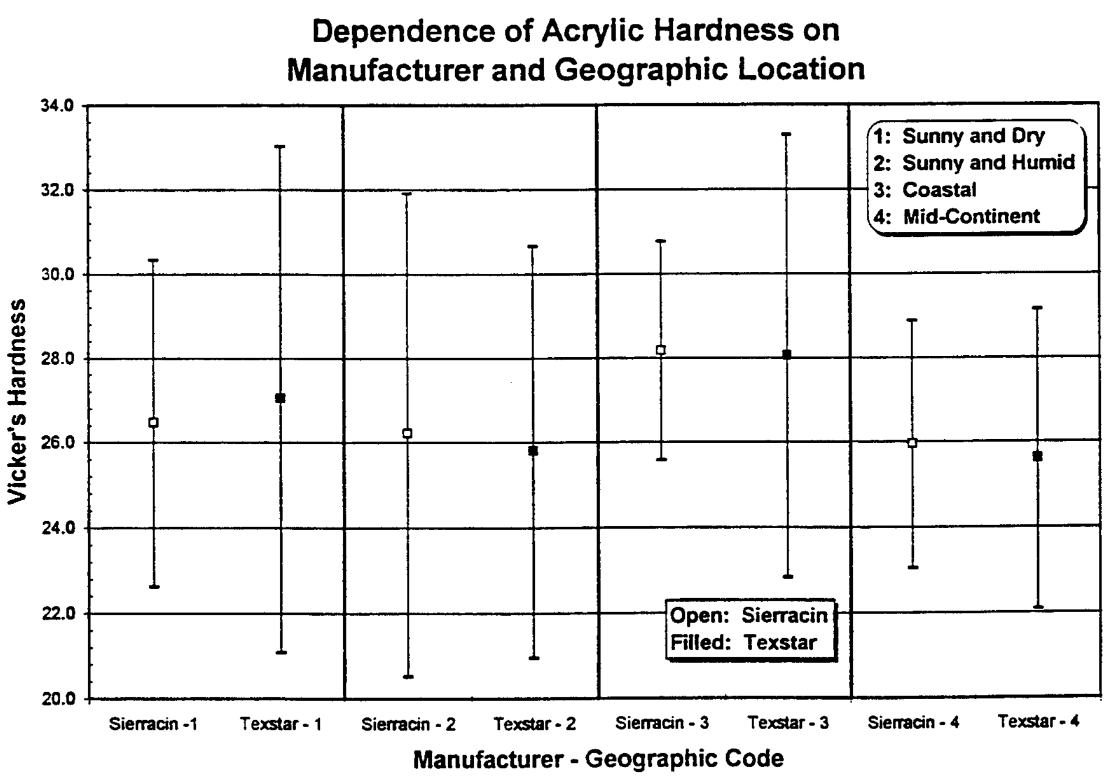


Figure 26. Manufacturer and Geographic Location Effects on Acrylic Hardness.

measurements from two specimens (six samples total). Hardness as a function of manufacturer and geographic location is given in Figure 26. Each point represents the mean of all hardness measurements from transparencies associated with the specific manufacturer and geographic location. Top and bottom bars represent the 2σ (standard deviation) limits from the mean. Figures 27 through 31 show hardness as a function of Total Radiation, Maximum Temperature, Total Degree Days, Number of Rainy Days, and Number of Clear days.

3.4.3.5. Data Analysis

Figures 24 and 25 indicate no discernible relationship between hardness and either service life or date of manufacture. Figure 26 also indicates no relationship between hardness and either manufacturer or geographic location when the data are pooled according to the categorization shown in Table 4. While trends in density and hardness were anticipated to be different, it appears that neither test produced results which could be correlated to any of the factors of interest. As in the density results, the large variation in the data (represented by the large error bars) is due primarily to variations in density between canopies, rather than variations between samples from the same canopy. Figure 32 demonstrates that 22 out of the 35 canopies tested had total variation (spread from $+2\sigma$ to -2σ) lower than the 5.2 total variation for Sierracin-3 (Figure 26), which had the lowest total variation for the groupings of Figure 32. Figure 32 further demonstrates the need for baseline data from each canopy if changes associated with aging are to be identified.

Figures 27-29 show no correlation between microhardness of coupons and Total Radiation, Maximum Temperature, and Degree Days, respectively. Texstar coupons show a <u>very</u> mild trend of increasing hardness with number of clear days. Increase in density is consistent with increased UV exposure and increasing number of clear days. However, the value of R^2 for the best fit is very low. For engineering purposes, $R^2 > 0.9$ is usually required for confidence that the fit represents the data. Note that Texstar coupons show no trends at all in the density data. Sierracin coupons showed a weak trend in hardness with Number of Degree Days.

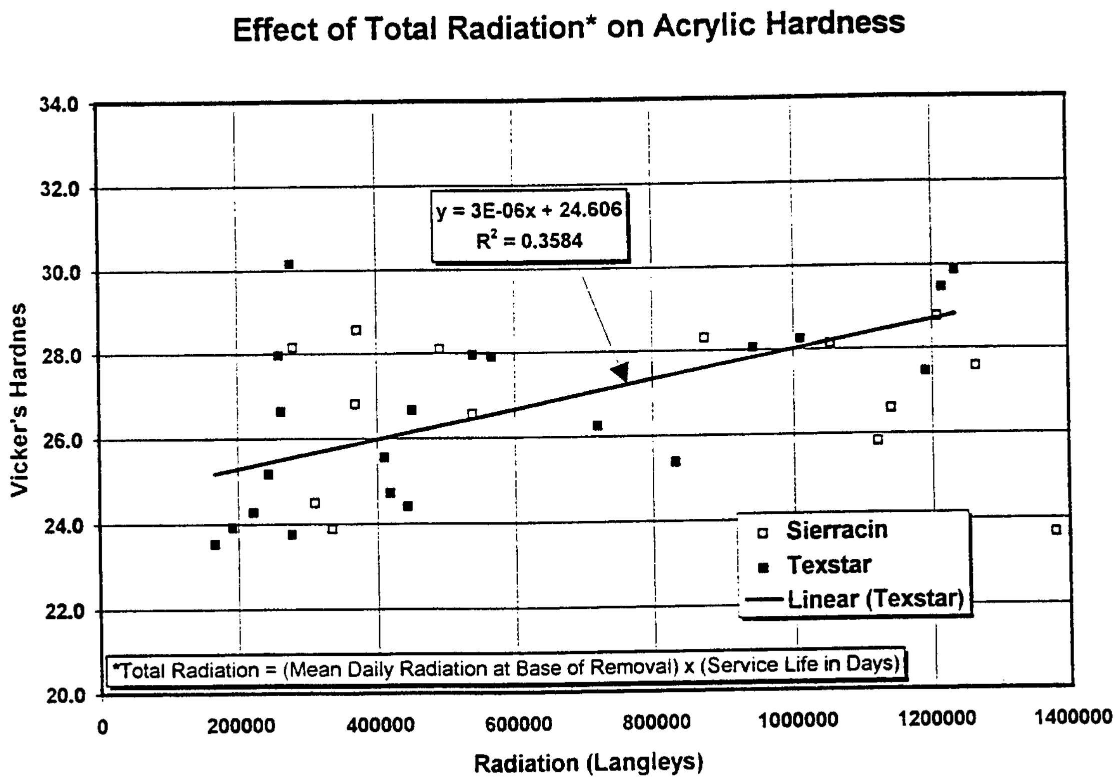


Figure 27. Total Radiation Effects on Acrylic Hardness.

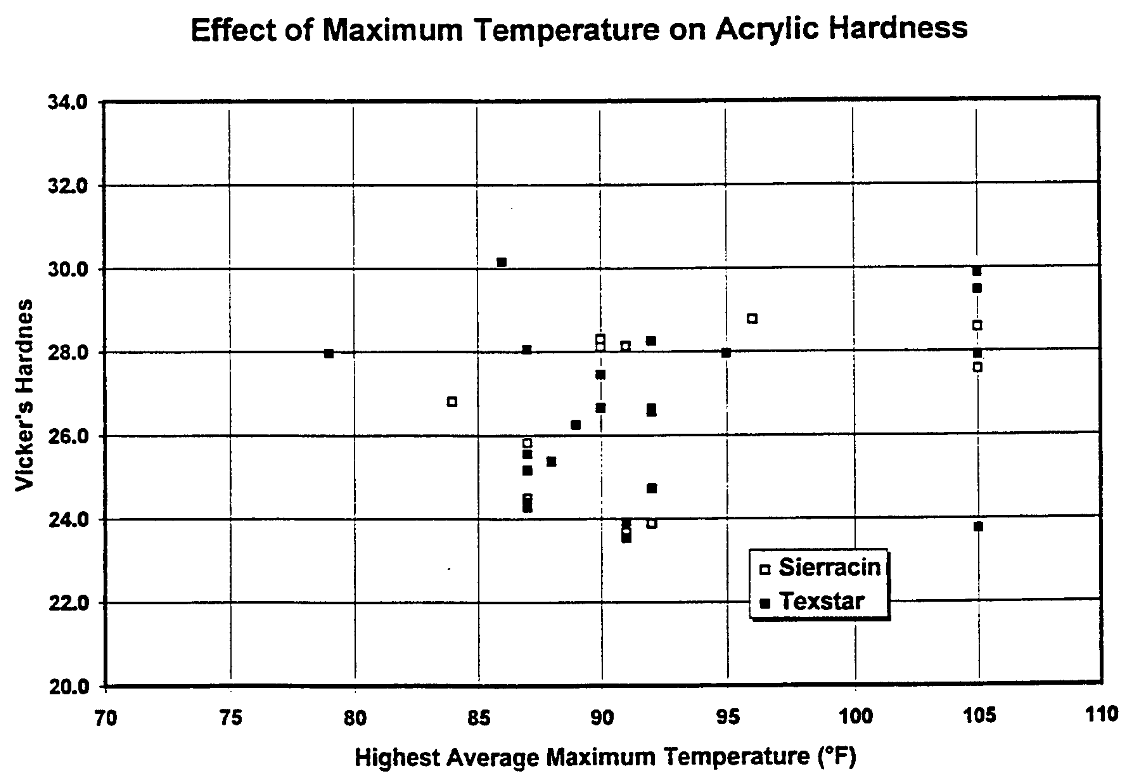


Figure 28. Maximum Temperature Effects on Acrylic Hardness.

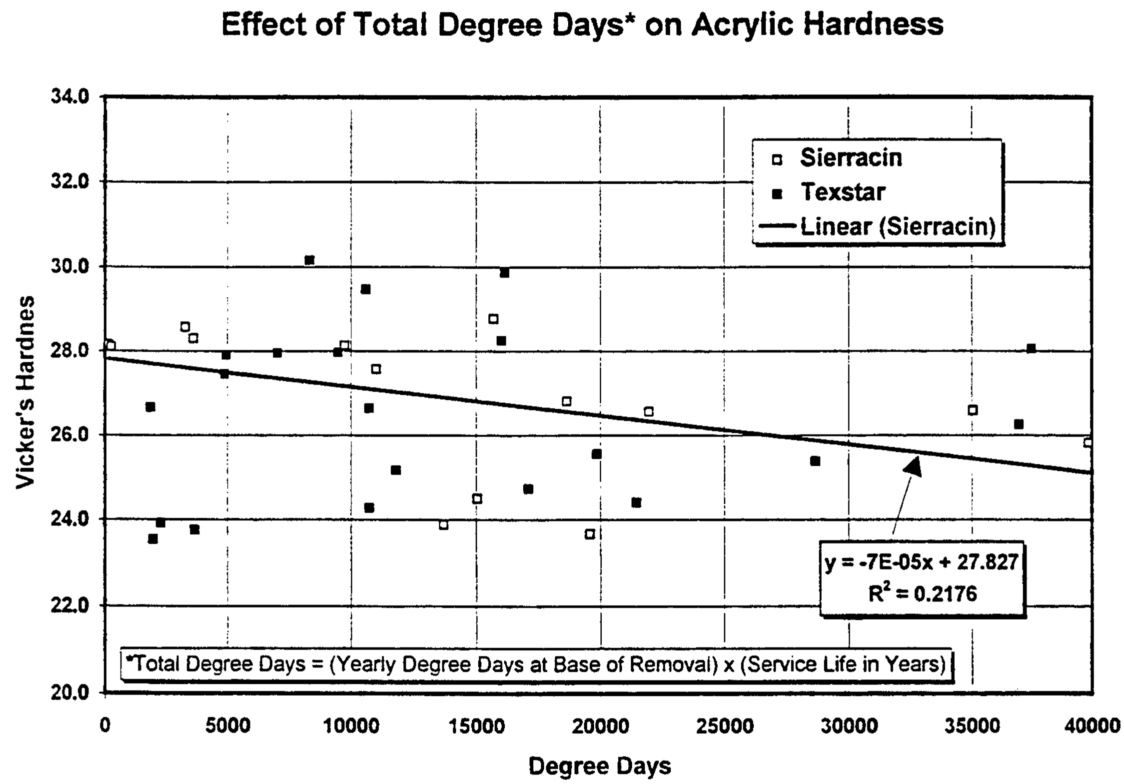


Figure 29. Degree Day Effects on Acrylic Hardness.

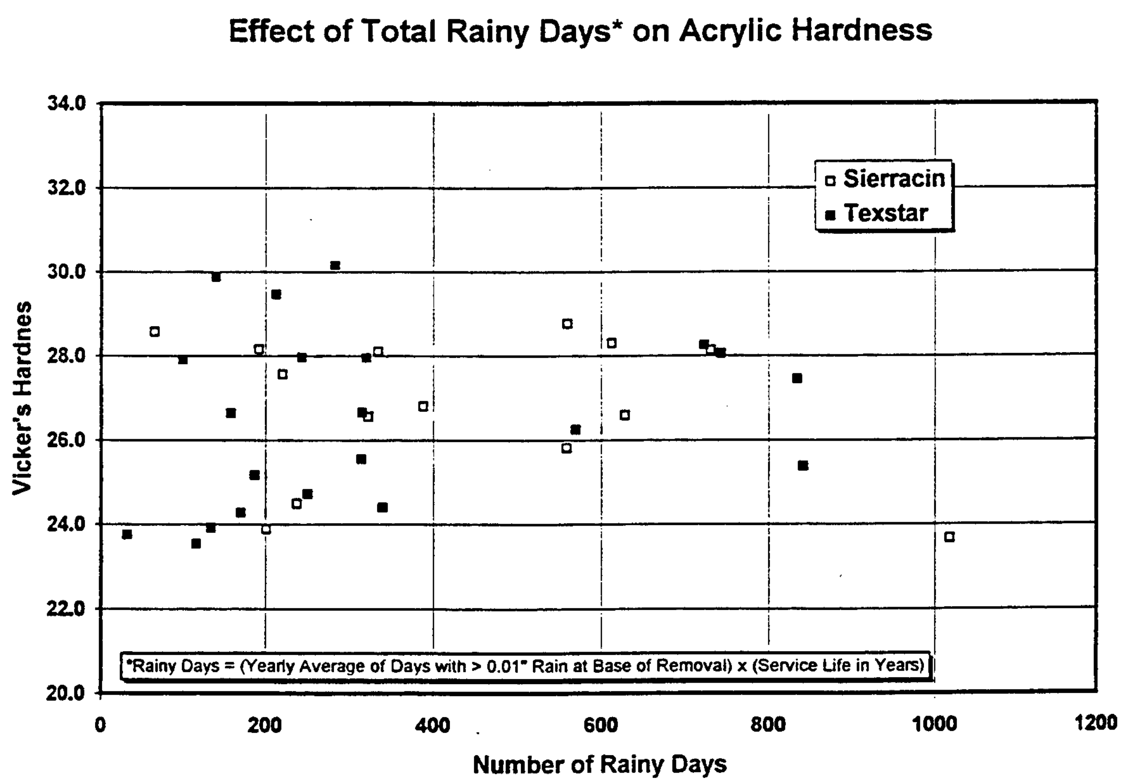


Figure 30. Rainy Day Effects on Acrylic Hardness.

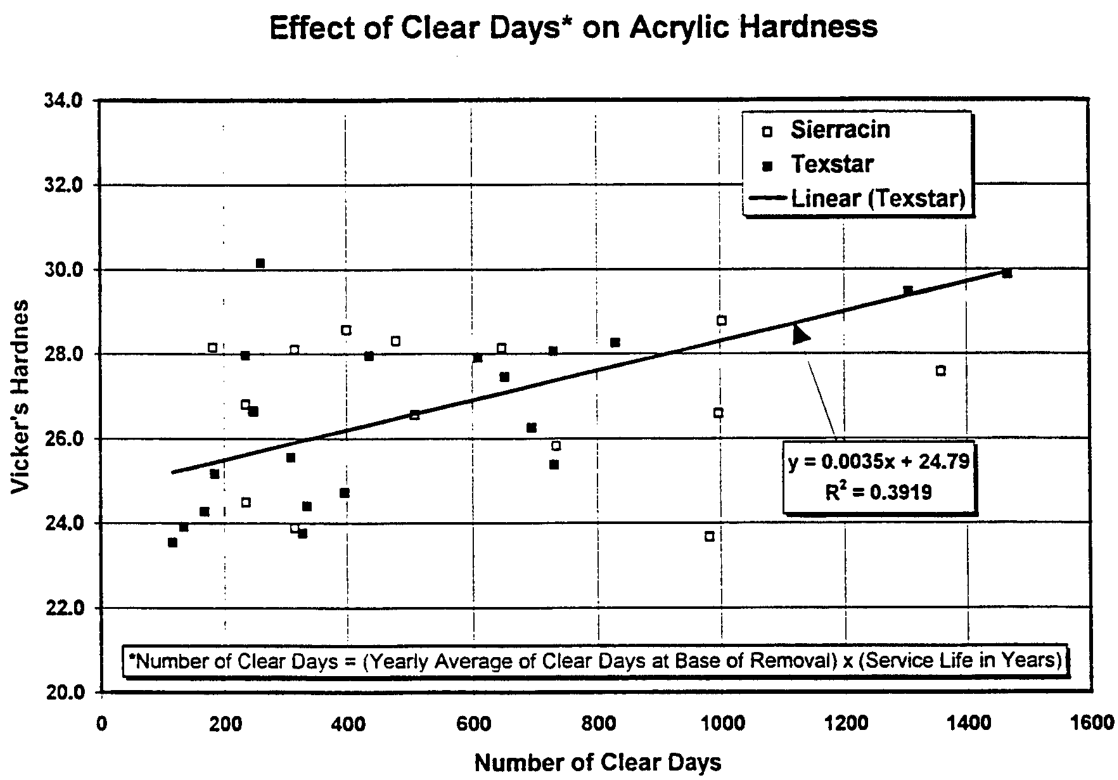


Figure 31. Clear Day Effects on Acrylic Hardness.

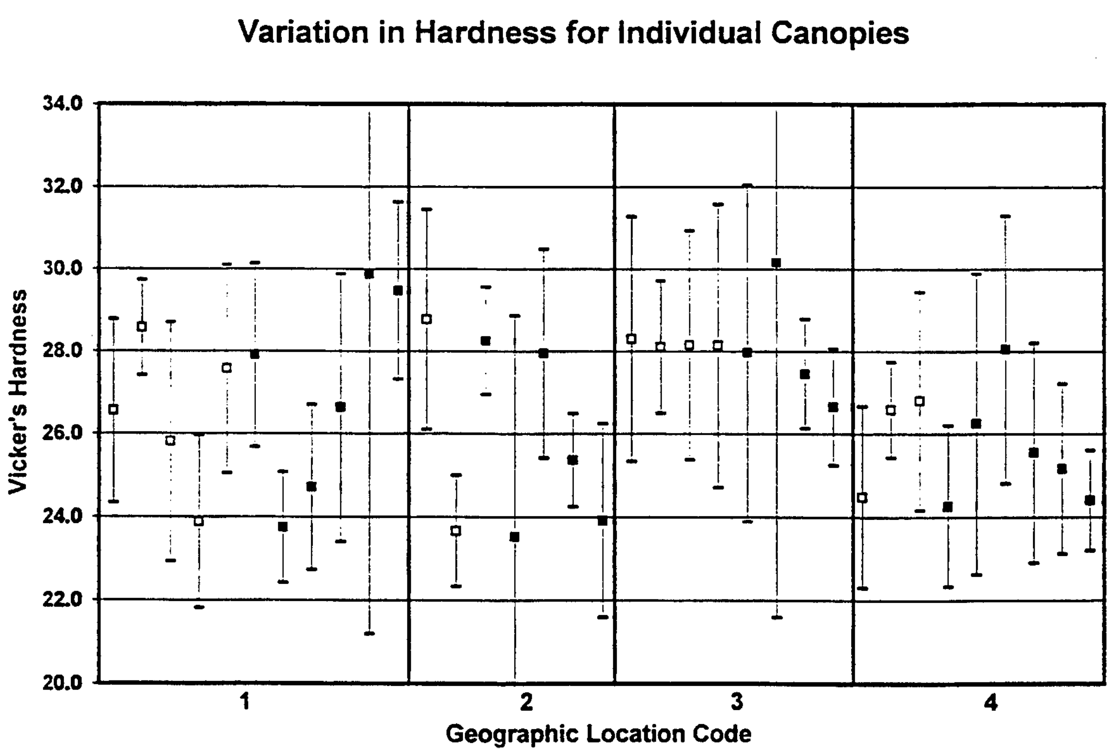


Figure 32. Variation in Acrylic Hardness Among Individual Canopies.

3.4.4. Chemical Stress Craze

3.4.4.1. Test Objective

The objective of this test was to investigate the resistance of the acrylic outer ply surfaces to chemical stress crazing. The best indication of craze resistance is a direct application of chemical while the material is under mechanical stress. Field service data indicates that crazing is a major cause of transparency removal and replacement. Crazing was selected as the focus of Phase III coupon tests.

3.4.4.2. Specimen Configuration

Test specimens consisted of cantilevered beams measuring 1.0 inch x 15.0 inch, rough cut and machined from the canopies listed in Table 1. The polycarbonate structural ply was removed by band-sawing the bulk of the polycarbonate from the acrylic, followed by belt-sanding to remove the remaining polycarbonate and interlayer. Curvature in the beams often made complete removal of the interlayer impossible. Samples with small amounts of interlayer remaining were not adversely affected since the interlayer stiffness is very low.

3.4.4.3. Test Method

The chemical stress craze tests were conducted utilizing ASTM F791 as a guideline. All testing was conducted at room temperature. The beams were loaded to produce a maximum stress at the fulcrum of 2500 psi for the majority of samples. After the load was applied, the beams were allowed to stabilize for 10 minutes before the test chemical was applied. A strip of filter paper 0.5 inch in width was placed along the center of each beam from the fulcrum to the point of load application. Chemical was applied to the filter paper, which kept the surface wetted and prevented chemical from contacting the machined edges of the beams and causing edge crazing. Advancement of the craze front along the beam length was monitored using a high intensity light from beneath the samples and visually inspecting through the filter paper. As the craze front advanced, the test beams were repositioned in the fixture such that stress in severely crazed portions of the beam was reduced while stress at the craze front was maintained (Figure 33). Repositioning the sample prevented craze near the fulcrum from advancing through the sample thickness and prematurely fracturing the sample. The filter paper was also repositioned by sliding the paper along the length of the beam to

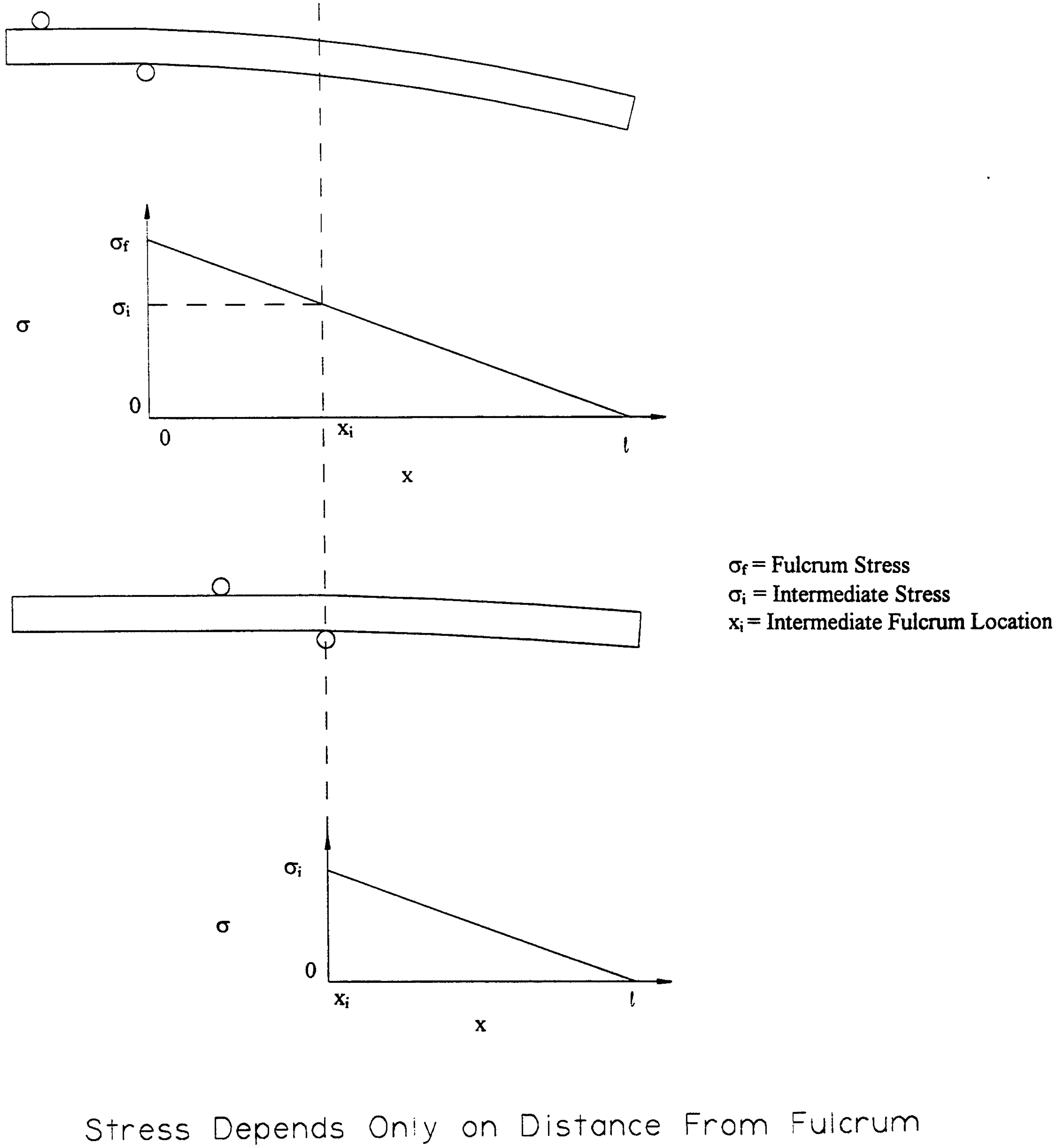


Figure 33. Repositioning of Craze Beams During Craze Testing.

remove chemical from the crazed areas. The test chemical was reapplied as required to maintain a wetted condition on the filter paper. Craze front location (corresponding to a discrete stress level) was recorded at the completion of the test, 30 minutes after initial chemical application. The test chemical was isopropyl alcohol.

3.4.4.4. Test Data

Average craze stress as a function of service life and date of manufacture are given in Figures 34 and 35. Each data point represents one canopy and is the average of between two and five samples. (Five samples from each canopy were tested; samples which fractured prior to 30 minutes of chemical exposure are not included in the data analysis.) Craze stress as a function of manufacturer and geographic location is given in Figure 36. Each point represents the mean of all craze stress measurements from a single transparency. For each manufacturer and geographic location, the canopy with short part life is on the left, the canopy with longer part life is on the right. Top and bottom bars represent the 2σ (standard deviation) limits from the mean. Figures 37 through 39 show craze stress as a function of Total Radiation, Number of Rainy Days, and Total Degree Days.

3.4.4.5. Data Analysis

Figures 34 and 35 indicate no discernible relationship between craze stress and either service life or date of manufacture. Figure 36 also indicates no relationship between craze stress and either manufacturer or geographic location when the data are pooled according to the categorization shown in Table 4. Note that in Geographic Locations 1, 2, and 3, the short part life canopy for each manufacturer has a higher mean craze stress than the longer part life canopy. However, as in the density and hardness results, large variation in the data (represented by the large error bars) prevents labeling this trend as significant.

Figures 37, 38, and 39 show no correlation between craze resistance of coupons and Total Radiation, Rainy Days, and Total Degree Days. Since these three factors represent the three primary variables of interest (radiation, moisture, and temperature) and no correlation was found with any of them, correlation of craze resistance to Clear Days and Maximum Temperature were not attempted.

Referring to Figure 36, the majority of craze stress values, including error bars, are in the range of 400 to 2000 psi, with means ranging from 800 to 1700 psi. An interlaboratory

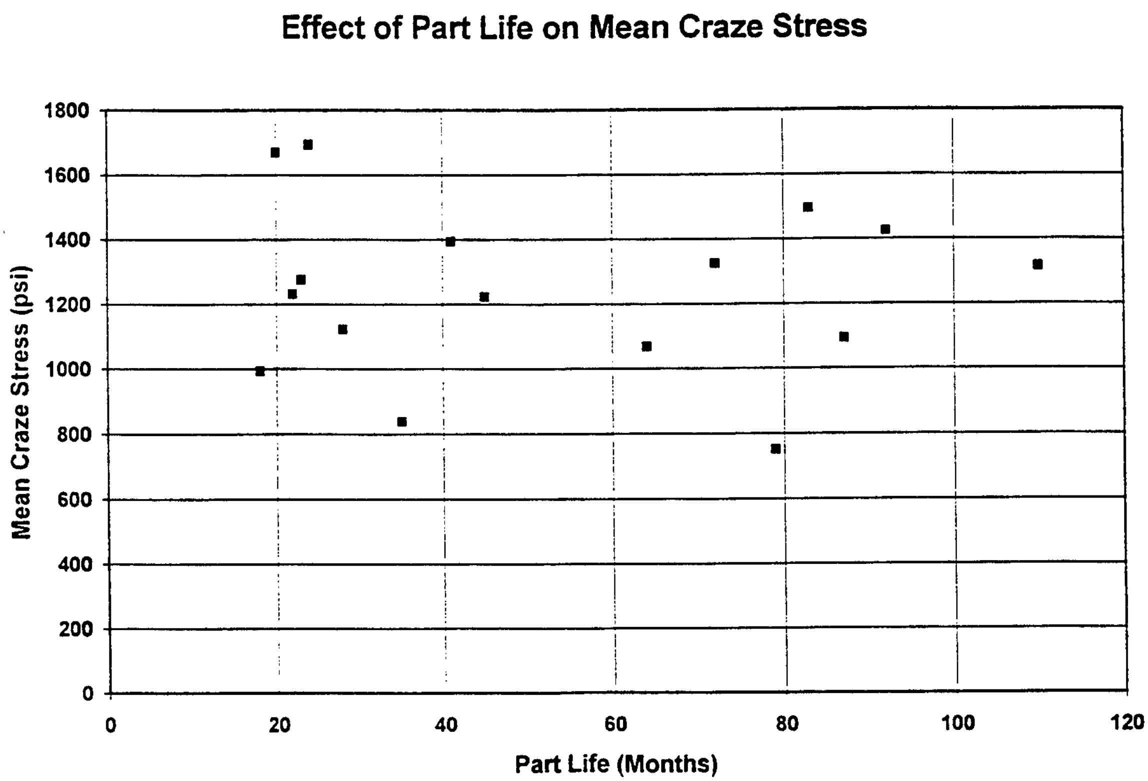


Figure 34. Part Life Effects on Chemical Stress Craze Resistance.

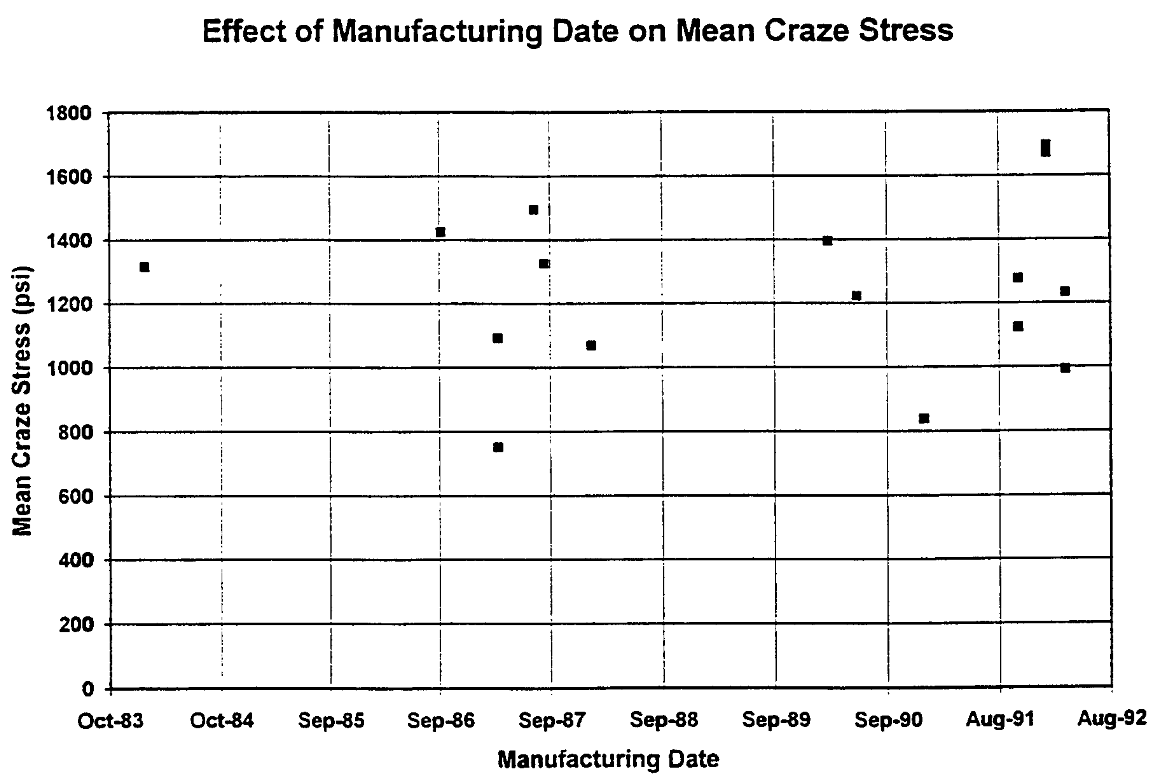


Figure 35. Date of Manufacture Effects on Chemical Stress Craze Resistance.

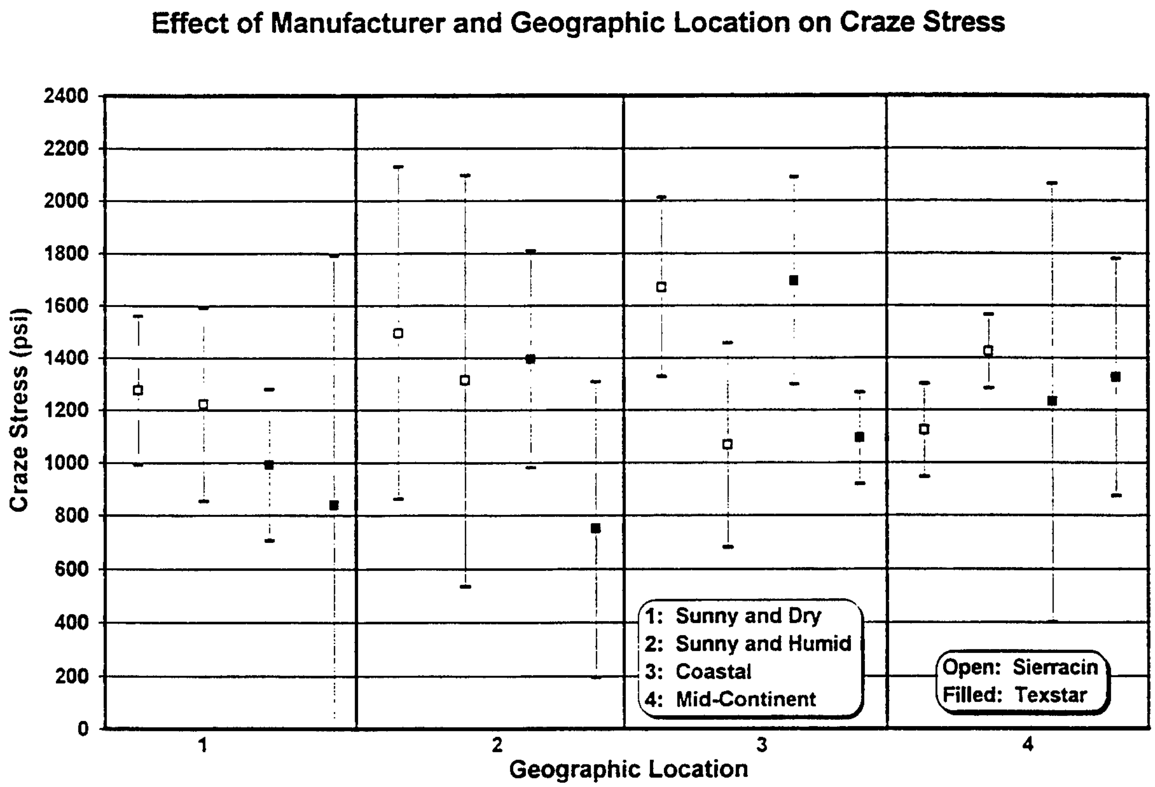


Figure 36. Manufacturer and Geographic Location Effects on Chemical Stress Craze Resistance.

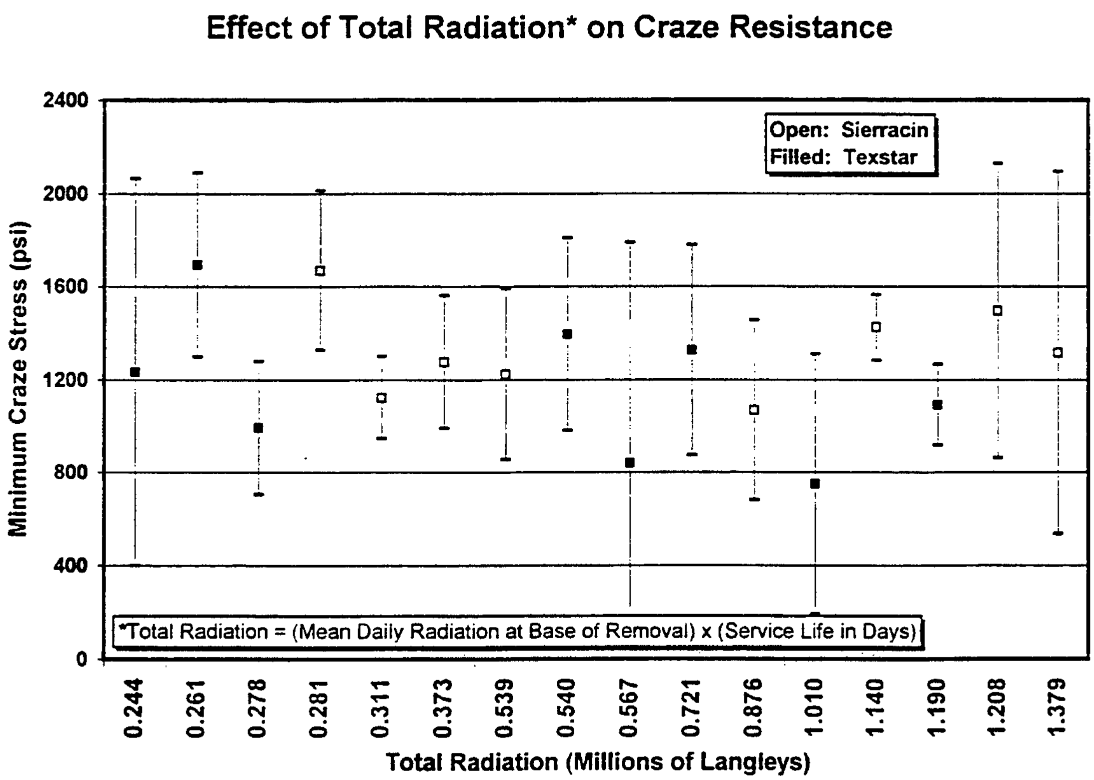


Figure 37. Total Radiation Effects on Chemical Stress Craze Resistance.

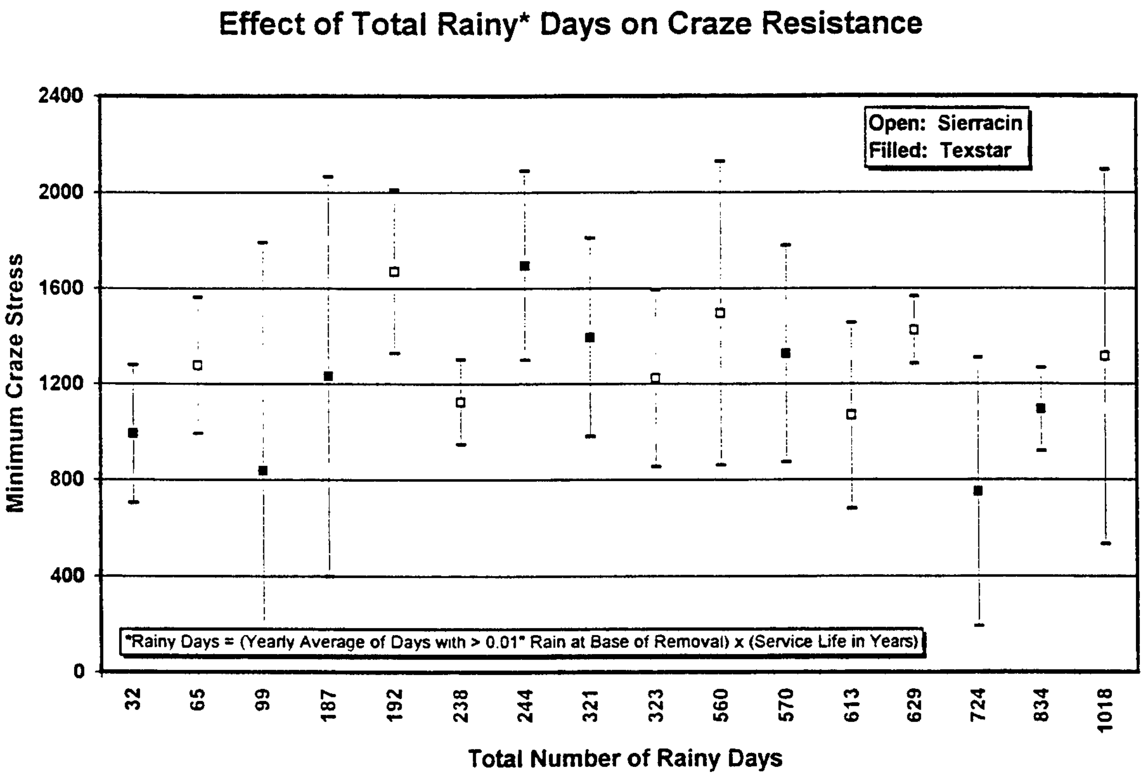


Figure 38. Rainy Day Effects on Chemical Stress Craze Resistance.

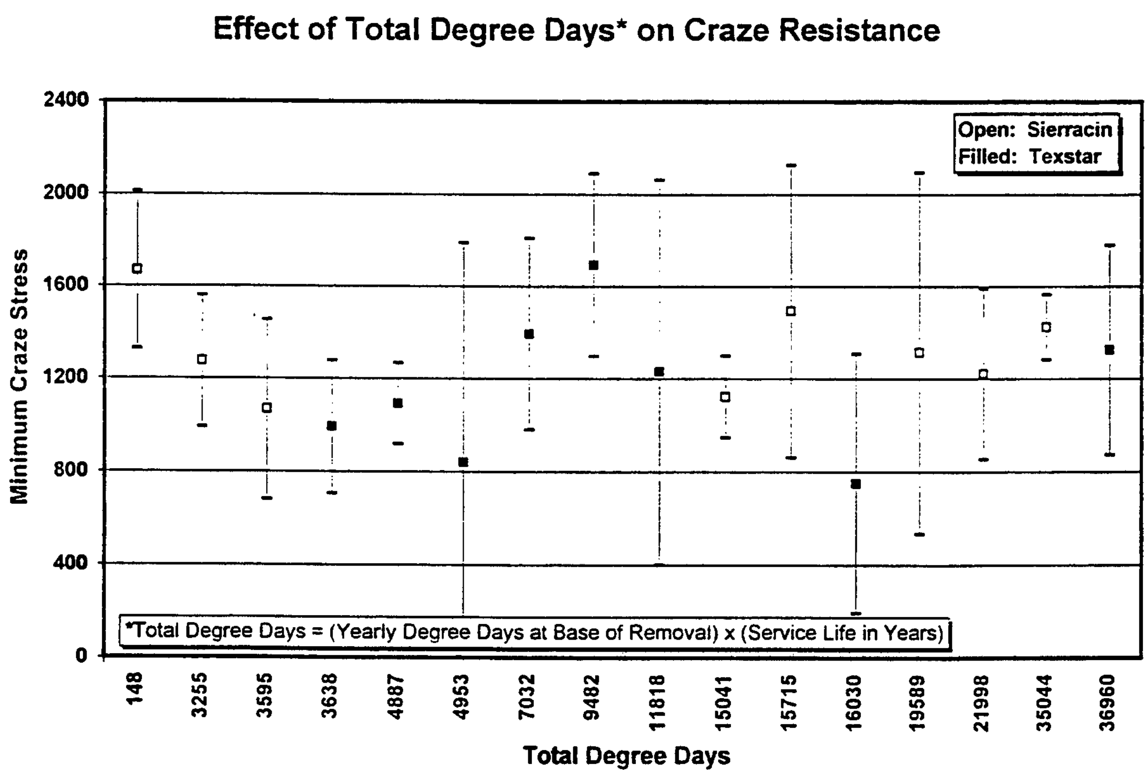


Figure 39. Degree Day Effects on Chemical Stress Craze Resistance.

study of ASTM Method F791 recently completed by Subcommittee F07.08 indicated minimum craze stress of 3180 ± 400 psi for cast acrylic with isopropyl alcohol. Phase I testing of the acrylic ply of new F-111 windshields indicated minimum craze stress of 1800 to 2600 for Sierracin windshields. Since all canopies in the current study failed due to craze and had minimum craze stress well below the minimum craze stress for baseline cast acrylic, a conclusion might be inferred regarding craze failure: F-16 canopies have a higher likelihood of "failure" (part removal) due to craze when the acrylic craze resistance is reduced from some mean baseline value to a mean value of 1700 psi.

The above statement will be discussed in Section 6, Conclusions and Recommendations.

3.4.5. Dust Exposure/Chemical Stress Craze

3.4.5.1. Test Objective

The objective of dust exposure is to simulate an environment in which a transparency may be subjected to repeated small particle impact and to assess the effect of exposure on craze resistance. QUV exposure has typically been used in the past to simulate the effect of outdoor exposure on material response. However, QUV exposure as an artificial weathering technique does not account for small, barely visible impact damage which is not severe enough to warrant part removal but which might influence craze resistance. Exposure of cast acrylic samples (no QUV exposure) to small dust particle erosion has not previously been combined with craze testing and provides additional information to define parameters which must be taken into account to reduce the incidence of craze.

3.4.5.2. Test Specimens

Test specimens consisted of 1-inch x 7-inch x 1/4-inch acrylic beams. Beams were rough cut from acrylic sheet (Section 3.3.2) and the edges milled to final dimension.

3.4.5.3. Test Method

Specimens were exposed to simulated dust environments in the WL/FIVE Dust Erosion Test and Analysis Facility following the proposed ASTM Test Method for Dust Erosion [13]. The facility (Figure 40) creates dust environments with control over velocity, mass flow rate,

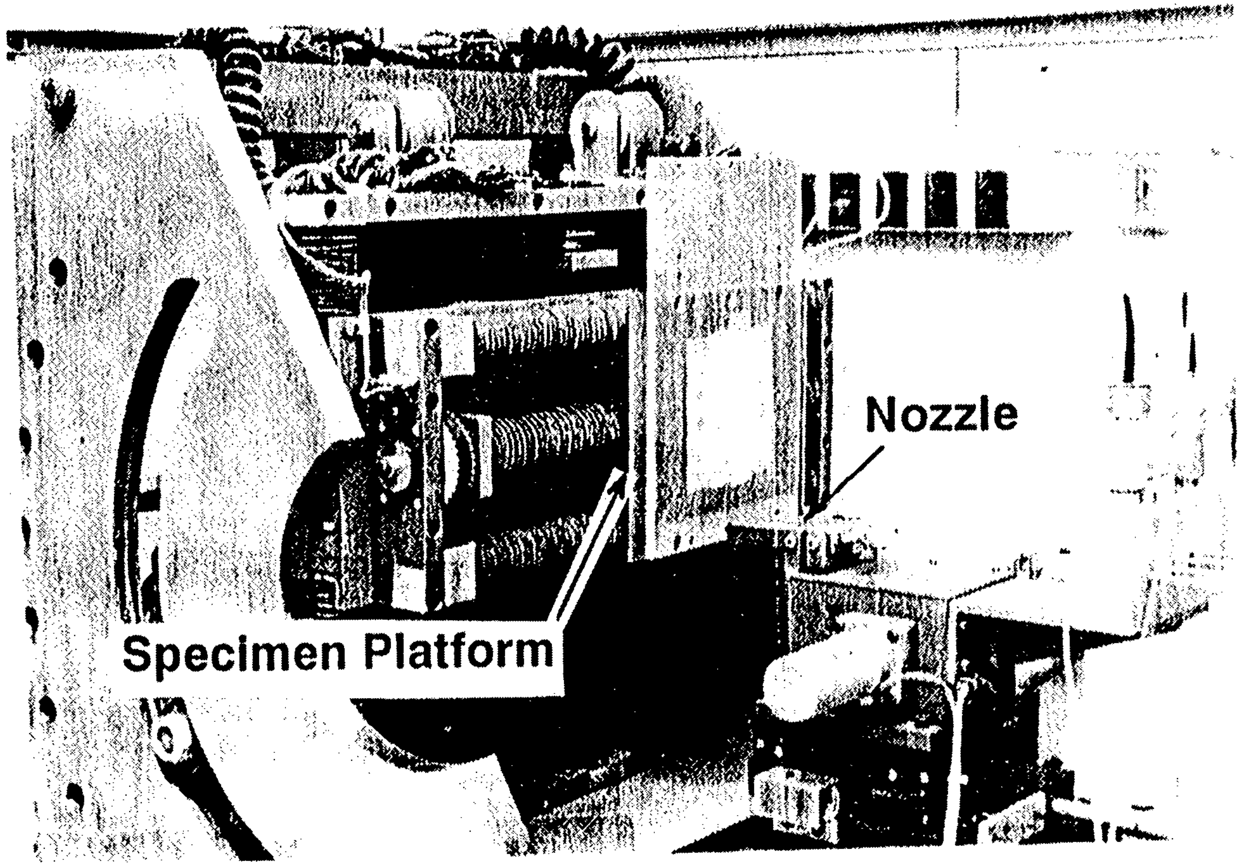


Figure 40. WL/FIVE Dust Erosion Test and Analysis Facility.

particle size, and impact angle. Three specimens were included for each exposure run. Table 7 gives the dust exposure conditions. The conditions were selected based on preliminary exposure of 2-inch-square samples which indicated the exposure level required for qualitatively different levels of visual damage. Haze and Transmittance were measured per ASTM D1003 prior to and after exposure runs and used as additional data for correlation. Chemical stress craze tests per paragraph 3.4.4.3 were conducted on each beam after exposure, with the exception that the specimens were reduced in length from 15 to 7 inches.

3.4.5.4. Test Data

Figure 41 shows a plot of minimum craze stress as a function of percent haze after dust erosion exposure. Each data point represents one craze beam. The abscissa for each point is the average of three haze readings taken along the length of the eroded area of each beam. The exposure condition is denoted by the type of symbol.

3.4.5.5. Data Analysis

Figure 41 shows a clear and identifiable trend indicating reduced craze resistance with progressively worse dust exposure (as quantified by percent haze). Figure 42 shows a least squares logarithmic trendline fit to the data, with a relatively high R^2 value of 0.85. While the R^2 value of 0.85 does not indicate that the specific logarithmic fit is correct, the value does lend evidence to a positive correlation. Figures 43 and 44 show photomicrographs of the surface of samples D-2, D-6, D-10, and D-22, indicating the types of dust erosion damage which are responsible for reduced craze resistance. Since damage sites are stress concentration points, a reduction in stress craze resistance to dust erosion exposure is reasonable. The photos in Figure 45 show that the damage sites are craze initiators, as crazing in dust exposed samples is more dense and less deep than crazing in baseline samples. The sensitivity of stress craze to dust exposure is a direct result of the presence of initiator sites.

Figure 41 indicates significant reduction in craze stress for haze values as low as 1.77%. Note the reduction in craze resistance quickly levels off with increasing haze after the initial steep drop. This pattern reflects the fact that the severity of damage is not as important to craze initiation as the simple presence of damage. In other words, once a few craze initiation sites are present and the applied stress is adequate, craze is likely to occur. As a result, samples with severe damage (as measured by haze) have craze resistance similar to

Table 7. Dust Erosion Parameters for Exposure of Craze Beams.

Condition	Velocity (m/s)	Loading (g/cm_2)	Particle Size (µm)	Angle (°)
A	257	0.0019	74-88	90
B	41	0.0104	74-88	90
C	41	0.0206	74-88	90
D	257	0.010	105-125	90

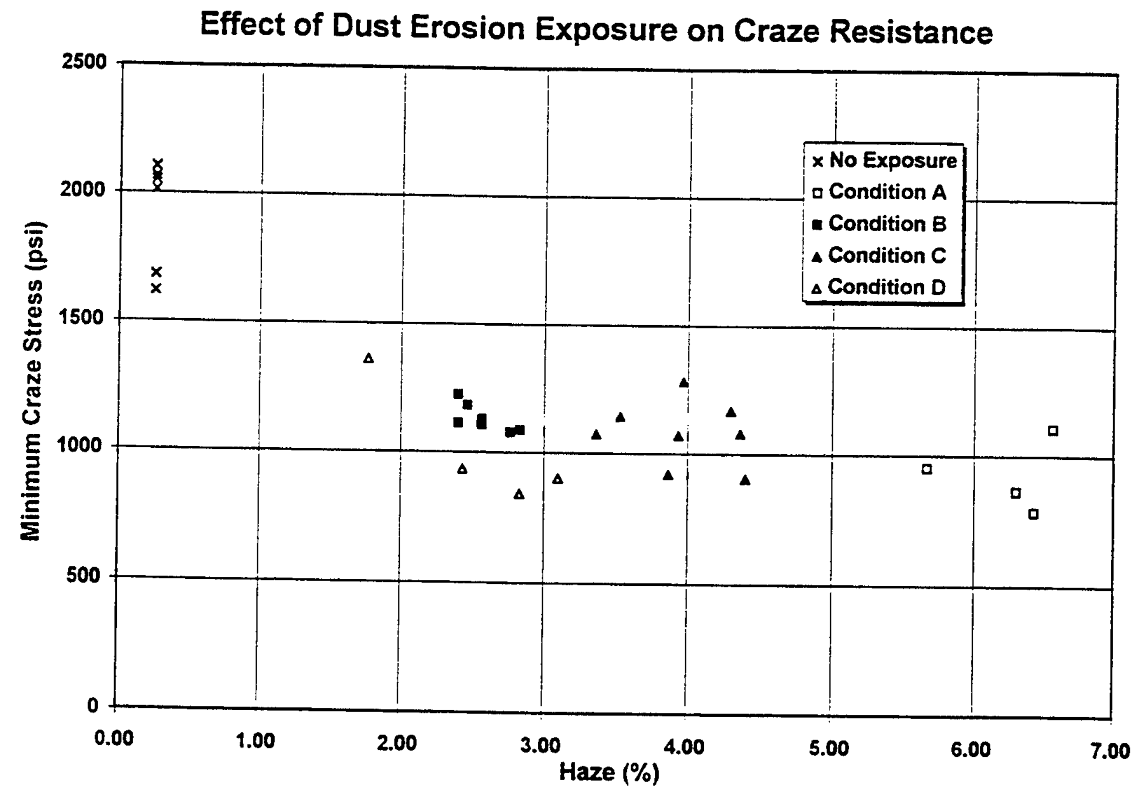


Figure 41. Effect of Dust Erosion on Minimum Craze Stress as Determined by Percent Haze.

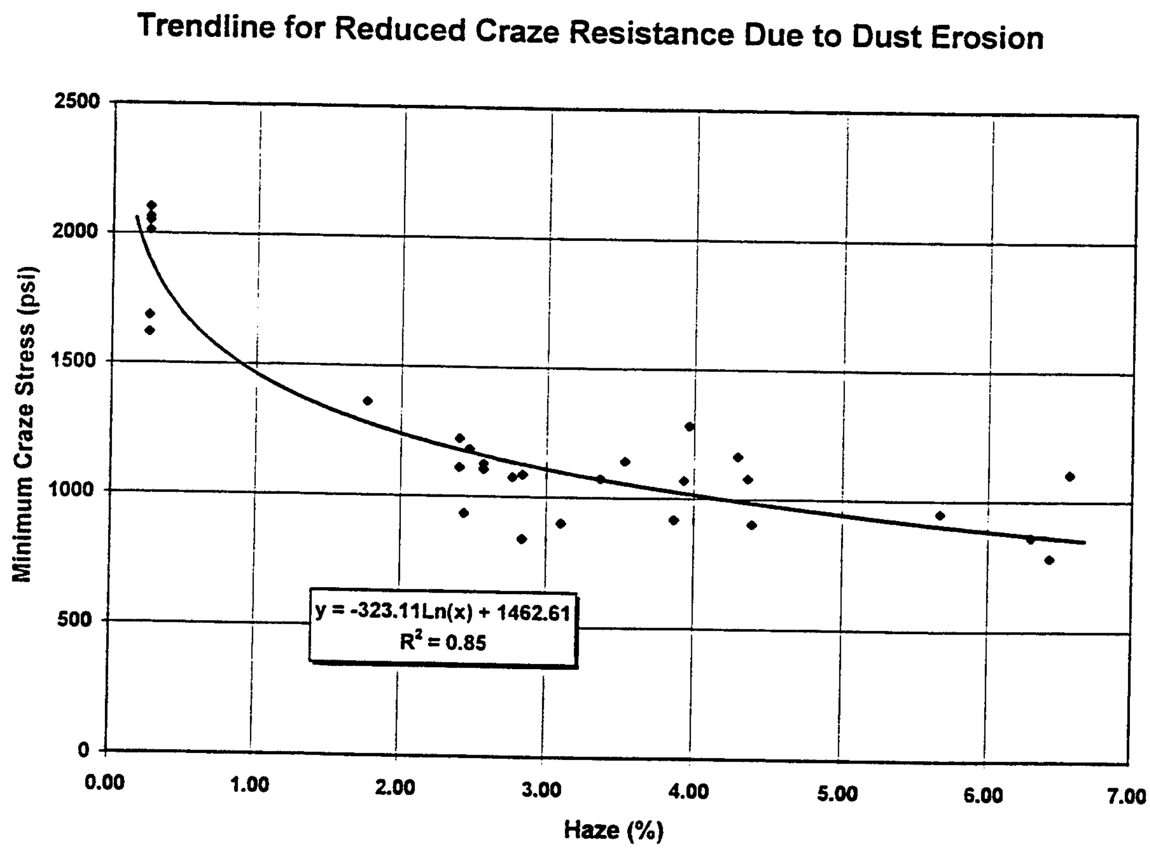


Figure 42. Craze Stress Modeled as Logarithmic Trend.

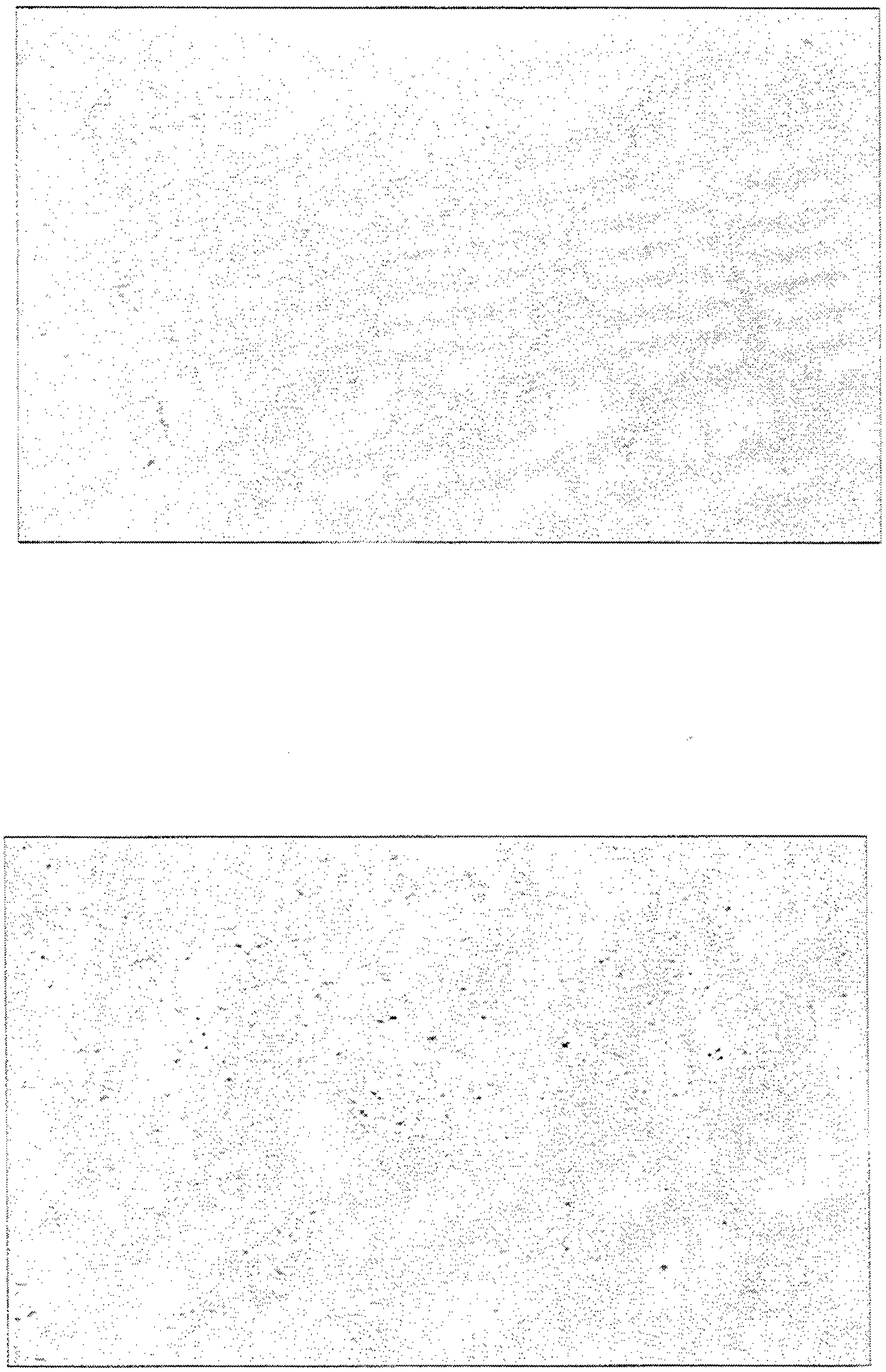


Figure 43. Photomicrographs of Samples D-6 and D-10 (Magnification 10x).

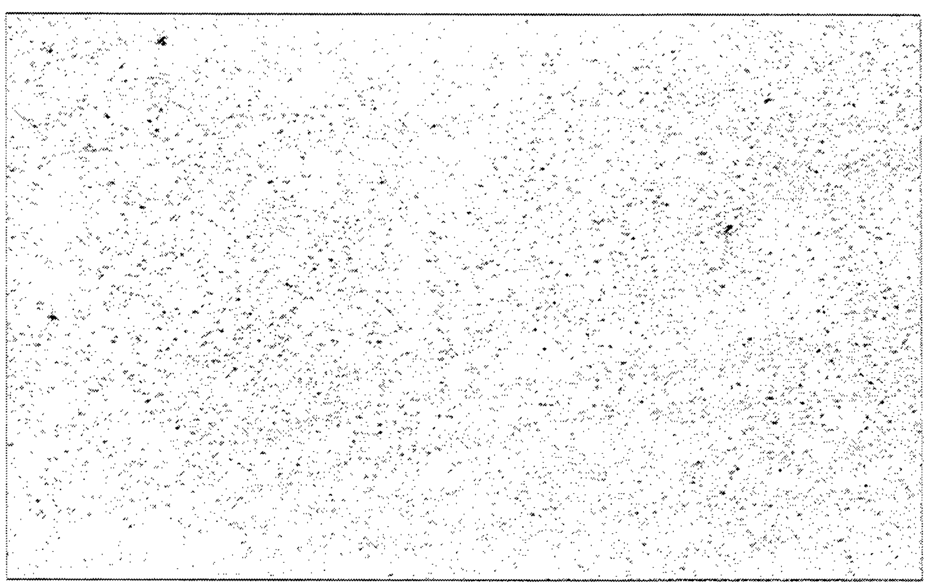
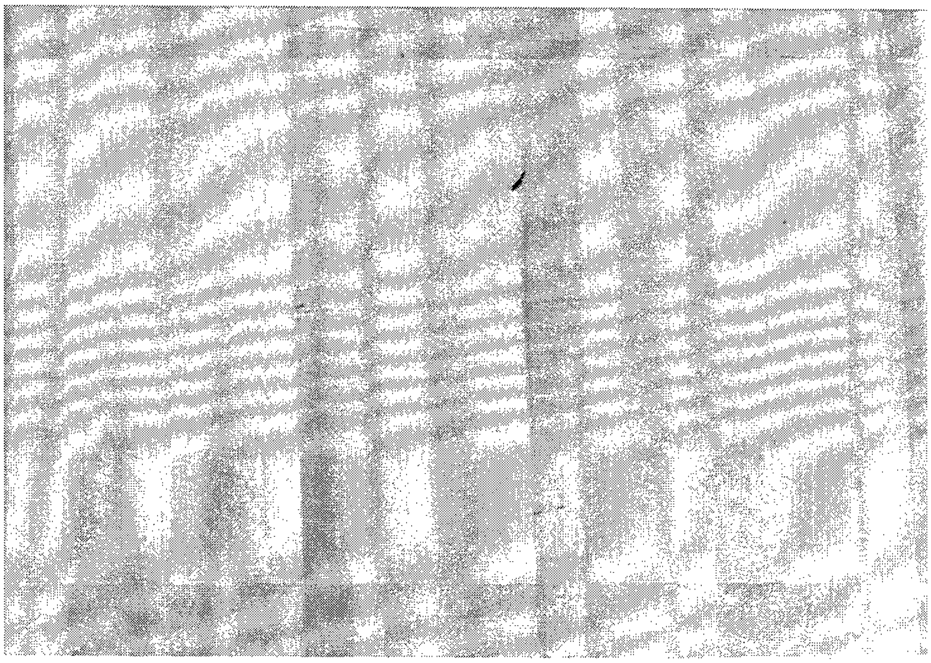


Figure 44. Photomicrographs of Samples D-2 and D-22 (Magnification 10x).



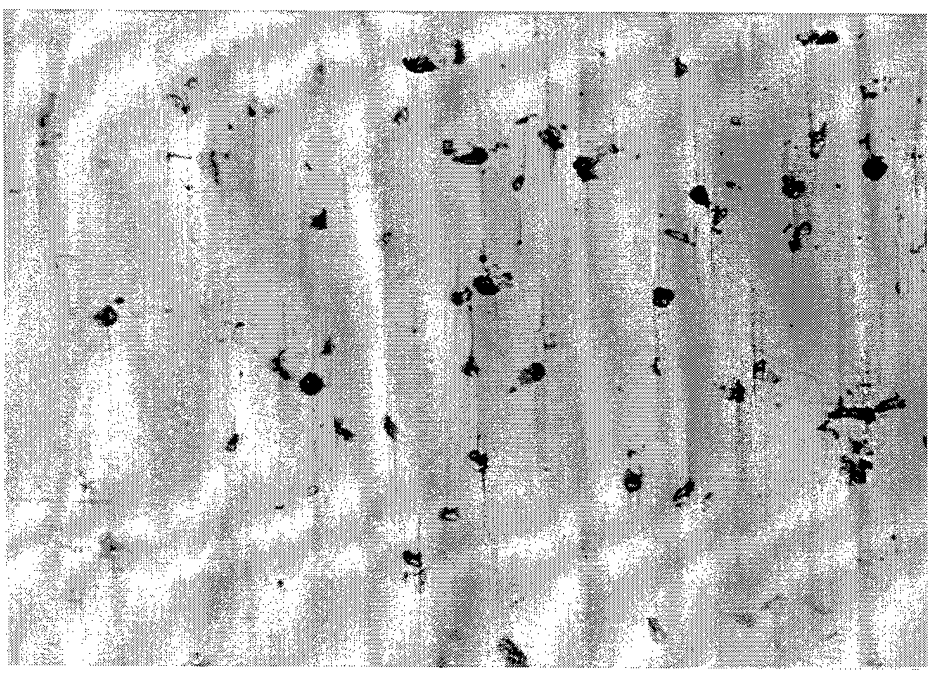


Figure 45. Comparison of Baseline and Dust Exposed Craze Beams (Magnification 100x).

samples with less severe damage. Such behavior is reflected in the data since this test is a measurement of craze initiation, and not of craze severity.

The data in Figure 41 are especially interesting when compared to haze data on transparency samples removed from the field. Although haze data were not collected in Phase III testing, baseline haze data were conducted on F-111 parts removed from the field for Phase II testing. Ninety-three percent (63/68) of the samples taken from the outer acrylic ply of these windshields had mean haze values in the 3-9 percent range. While haze is not an indicator of dust-erosion damage alone (scratches and other factors influence haze readings), it is clearly possible that erosion damage severe enough to reduce craze resistance may exist on many canopies in the field. As the photomicrograph in Figure 44 indicates, mild damage is difficult to record microscopically. It is even more difficult to detect visually. As a result, the presence of mild (but optically acceptable) erosion damage may be a large contributor to the likelihood that a canopy may fail due to craze.

Because dust exposure is seen to reduce craze resistance, the durability of future materials and coatings may be better forecast by conducting a series of light dust erosion exposures followed by microscopic examination for initiaton sites. Materials which are resistant to erosion damage will be less likely to craze than a less erosion resistant material given identical exposure to other environmental factors (chemical, UV, heat, etc.).

The data in Figure 41 also indicate that the dust erosion technique produces consistent damage in terms of haze. Haze values are grouped tightly for each exposure condition, which is consistent with previous exposure work using this apparatus [12]. The facility could be used to further investigate the role of specific exposure conditions on craze resistance by monitoring the exposure time required to produce initiaton sites or reduce craze resistance. A judgment of erosion response of a material or severity of conditions could then be made based on craze resistance (which is more directly related to transparency removal) rather than haze.

3.4.6. Water Drop Impact (Rain) Exposure/Chemical Stress Craze

3.4.6.1. Test Objective

The objective of rain exposure is to simulate an environment in which a transparency may be subjected to water drop impact and to assess the effect of exposure on craze resistance. Exposure of cast acrylic samples (no QUV exposure) to water drop erosion has

not previously been combined with craze testing and provides additional information to determine which parameters must be taken into account to reduce the incidence of craze.

3.4.6.2. Test Specimens

Test specimens consisted of 1-inch x 7-inch x 1/4-inch acrylic beams. Beams were rough cut from acrylic sheet (Section 3.3.2) and the edges milled to final dimension.

3.4.6.3. Test Method

Specimens were exposed to simulated rain drop impact in the UDRI Water Jet Impact Facility (Figure 46), located on the campus of the University of Dayton. The apparatus creates jets of water with control over velocity, jet size, and impact angle. The apparatus has been calibrated over three velocity ranges so that damage imparted by the water jet is identical to the damage created by the whirling arm facility at Wright Laboratory. The whirling arm facility produces drops with diameters between 1 mm and 2 mm. The Water Jet Impact Facility shoots a single jet of water. Multiple impacts are created by reloading and shooting. The device can be used to control impact location, which permits identification of craze initiation originating from impact locations.

The matrix of samples and velocities is shown in Table 8. Three samples were water jet impacted at each of four velocities for a total of 12 samples. Four impacts (at the same velocity) were conducted on each sample as shown in Figure 47, resulting in impact sites at four discreet stress-level locations on each sample. Impact site dimensions were recorded and photographed on one sample from each velocity group. Visual inspection of each impact site was conducted and recorded to note differences in impact appearance between impacts at similar velocities.

Chemical stress craze tests per paragraph 3.4.4.3 were conducted on each beam after exposure, with the exception that the specimens were reduced in length from 15 to 7 inches.

3.4.6.4. Test Data

Impact site dimensions, obtained from optical image analysis, are given in Table 9. Figures 48-51 show typical photomicrographs of the impact sites. Note the microcrazing and microcracking which occurs in and around the damage sites, even at low (200 m/s) velocity.

Table 8. Test Parameters for Water Jet Impact Testing.

Gun Pressure (psi)	Velocity (m/s)	Velocity MPH	Sample-Site	Damage*	Comments
100	500	1118.5	501-1	E	19-1/2" Barrel
100	500	1118.5	501-2	E	1/16" Off Center Vert.
100	500	1118.5	501-3	E	
100	476	1065	501-4	Fair	
100	500	1118.5	502-1	E	
100	500	1118.5	502-2	E	
100	500	1118.5	502-3	E	
100	536	1198	502-4	E	
100	509	1138	503-1	E	
100	500	1119	503-2	G	
100	500	1119	503-3	VG	
100	500	1119	503-4	E	
76	400	895	401-1	E	#2 Cylinder Gun Tilt. Piston PFP Pellet 10-1/2" Barrel
76	405	707	401-2	E	Piston = 1.40gm
76	380	850	401-3	E	
76	395	883	401-4	E	
75	395	883	402-1	E	10-1/2" Barrel
75	400	895	402-2	E	
75	370	829	402-3	E	
75	370	829	402-4	E	
75	448	1002	403-1	E	
75	462	1032	403-2	E	
75	429	959	403-3	E	
75	414	926	403-4	E	
68	286	639	301-1	VG	Pellet RWS S.P. 10-1/2" Barrel Long Inconel Piston @ 3.1gm Mass
68	286	639	301-2	G	#2 Cylinder and Nozzle
68	291	652	301-3	VG	
68	297	665	301-4	F	
68	313	699	302-1	E	PFP Pellet - 14-1/2" Barrel
68	289	645	302-2	E	

Table 8. Test Parameters for Water Jet Impact Testing. (Concluded)

Gun Pressure (psi)	Velocity (m/s)	Velocity MPH	Sample-Site	Damage*	Comments
68	309	692	302-3	G	
68	316	706	302-4	VG	
76	300	671	304-1	F	15-1/2" Barrel - #1 Cylinder and Nozzle White Inconel Piston
76	300	671	304-2	G	With .60 + 5.6gm added
76	300	671	304-3	VG	
76	297	665	304-4	G	
76	204	457	201-1	VG	Cylinder #1 Nozzle Plate #1 White Inconel Piston 1.40gm + .60 Striker +
76	196	439	201-2	VG	5.6gm mass = 7.60gm, RWS S.P. Pellet - Barrel - 9-1/2" Long
76	196	439	201-3	VG	
76	207	463	201-4	VG	
76	188	419	202-1	VG	
76	194	433	202-2	VG	
76	203	453	202-3	VG	
76	200	447	202-4	VG	
76	201	450	206-1	G	
76	210	469	206-2	G	
76	201	450	206-3	G	
76	208	466	206-4	G	

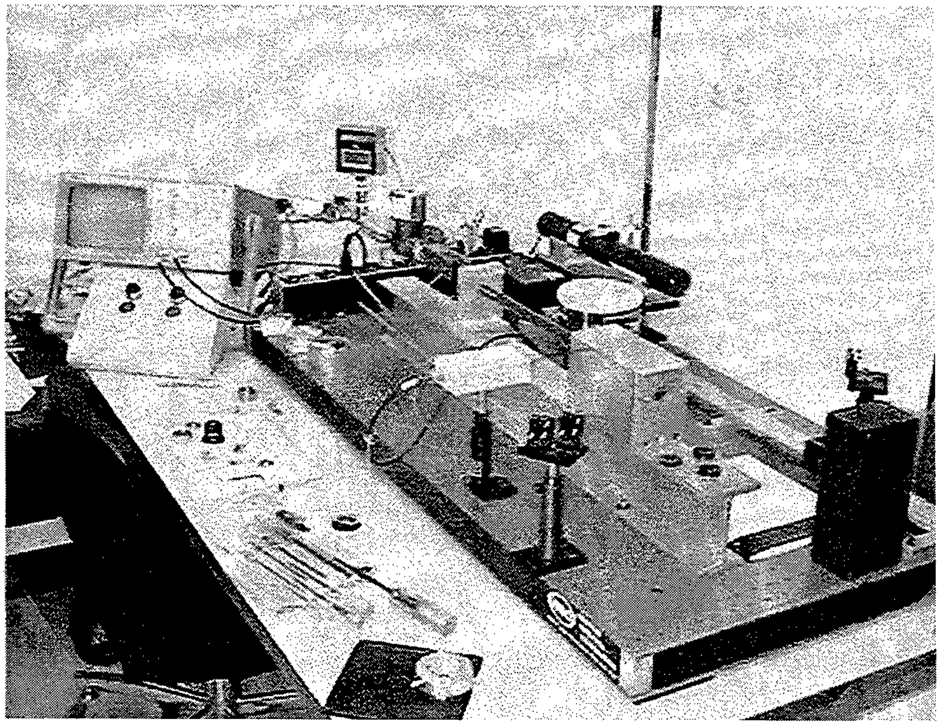
* Damage refers to uniformity of damage crater: E = Excellent, VG = Very Good, G = Good, F = Fair

Table 9. Water Impact Site Dimensions.

IMPACT SITE DAMAGE MEASUREMENTS

VELOCITY (m/s)	VELOCITY (knots)	MINIMUM DIAMETERS (microns)	MAXIMUM DIAMETERS (microns)	AVERAGE DIAMETERS (microns)	ROUNDNESS**
200	389	486.52	566.88	520.99	1.2407
300	583	567.84	793.19	679.59	1.2715
400	778	840.42	912.27	871.69	1.2313
500	972	931.83	1018.59	982.20	1.2213

** Roundness = (perimeter^2)/(4 π (area))
circular = 1
other shapes > 1



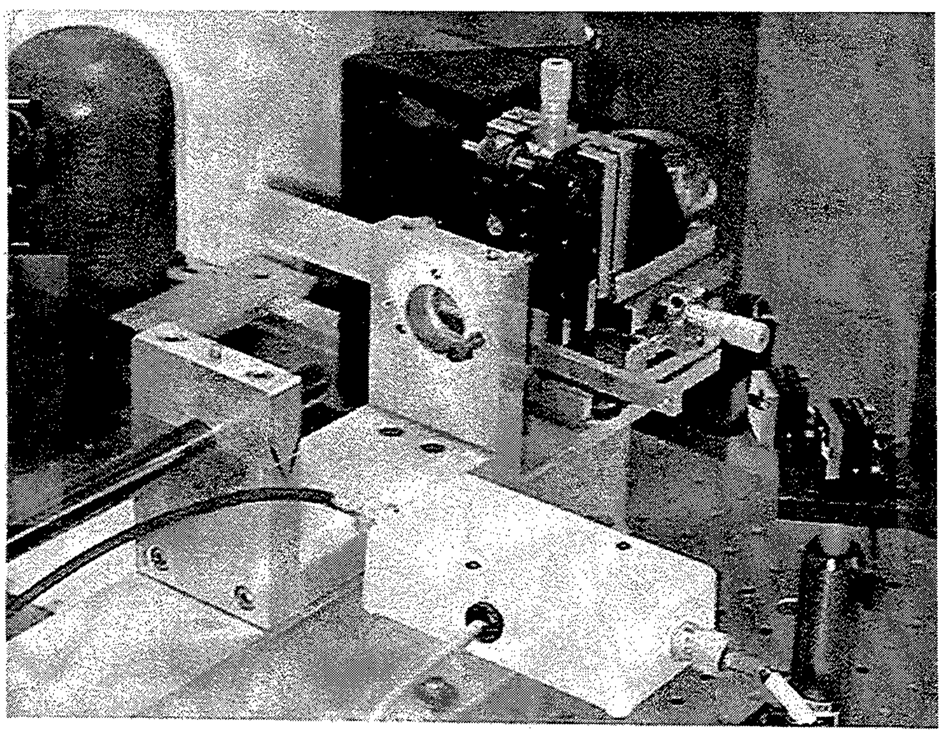


Figure 46. UDRI Water Jet Impact Apparatus.

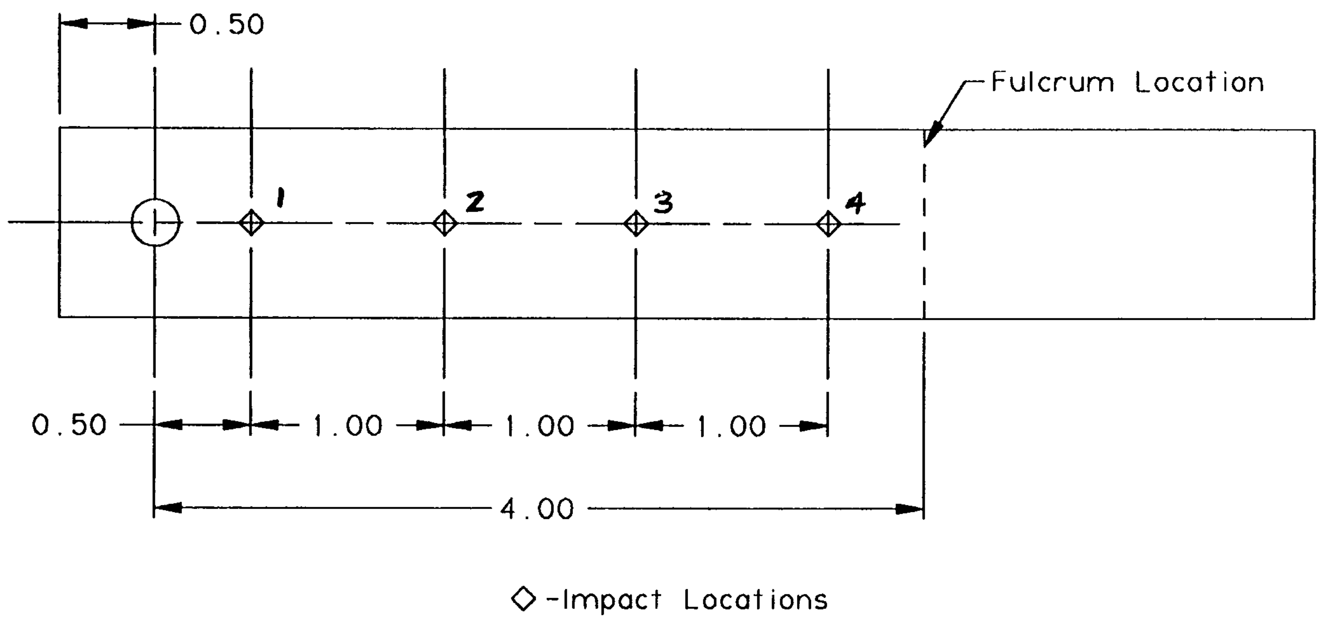


Figure 47. Water Jet Impact Locations.

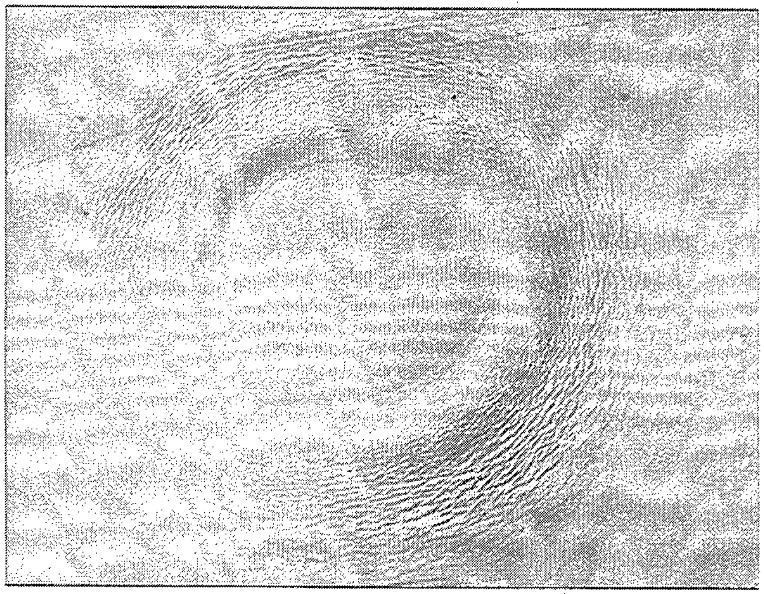


Figure 48. Photomicrograph of 200 m/s Water Impact Damage on Acrylic (Magnification 100x).

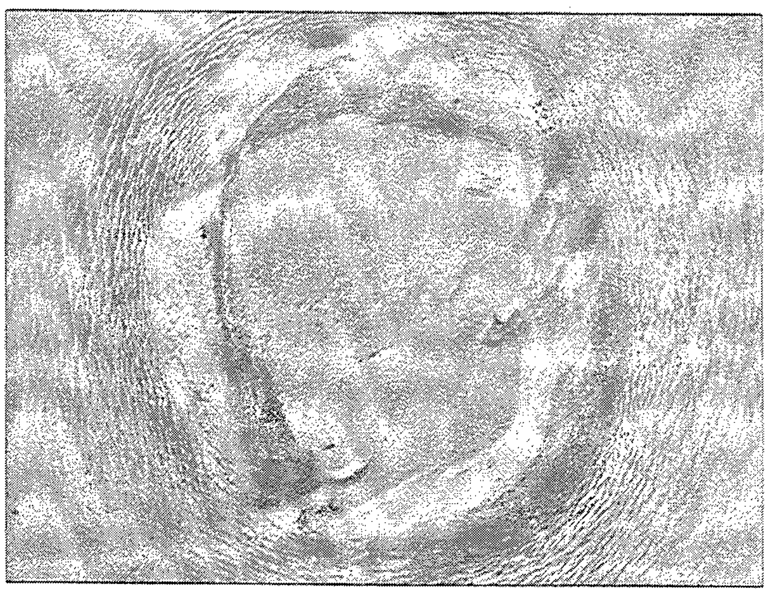


Figure 49. Photomicrograph of 300 m/s Water Impact Damage on Acrylic (Magnification 100x).

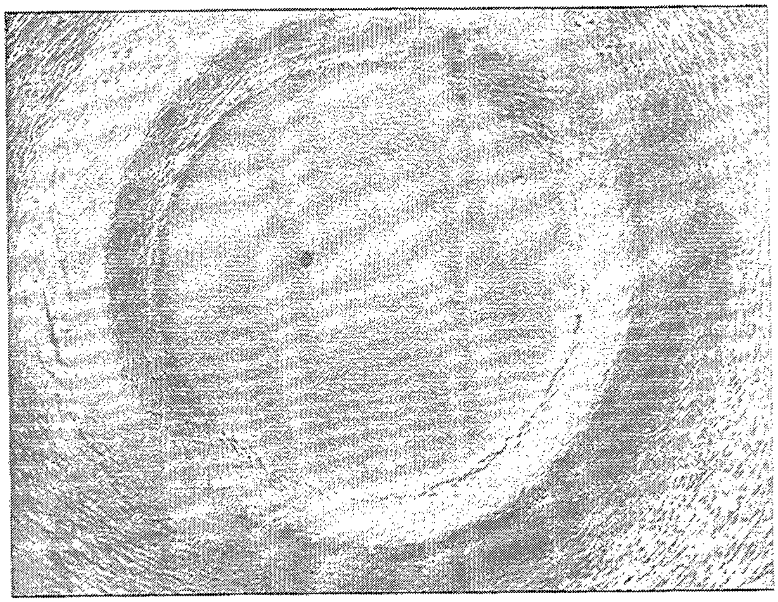


Figure 50. Photomicrograph of 400 m/s Water Impact Damage on Acrylic (Magnification 100x).

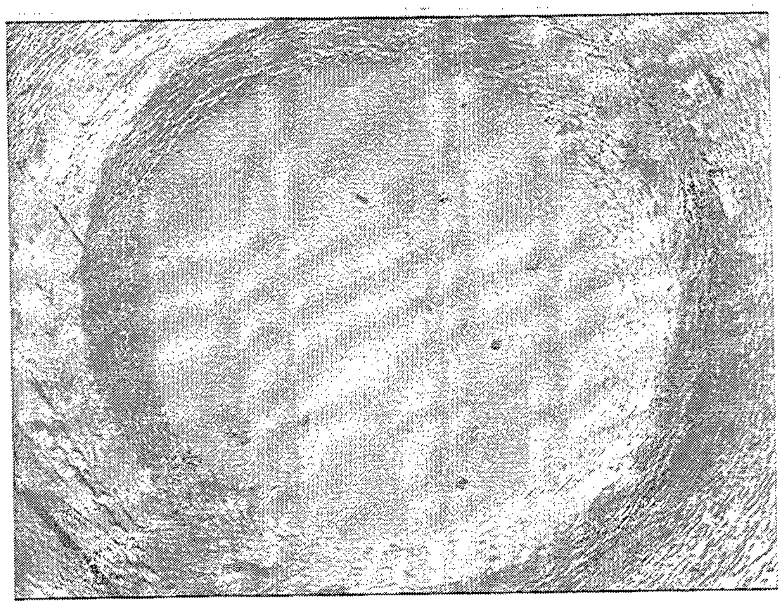


Figure 51. Photomicrograph of 500 m/s Water Impact Damage on Acrylic (Magnification 100x).

Minimum stress to craze data are listed in Table 10. Table 10 shows the point to which the craze front progressed down the beam, as well as the farthest point down the beam at which craze formed around a water impact site, if the site was farther down the beam than the craze front. Figure 52 shows the craze formation on sample 401, which is typical of craze formation on the other samples.

3.4.6.5. Data Analysis

Table 10 demonstrates that damage caused by water impact at sufficiently high velocity will reduce craze resistance of acrylic. In this study, water impact at velocities greater than 300 m/s reduced the craze resistance from about 1400 psi to 1000 psi. The latter number could be lower if the impact site had been located farther down the beam. Likewise, water impact at 200 m/s may have shown reduced craze if impact sites had been located farther toward the fulcrum. Since the impact sites were located at specific stress levels on the beams, the minimum stress for the specific impact site cannot be determined from this data. However, the data lend evidence to the hypothesis that barely visible water impact damage can contribute to transparency removal due to craze by creating initiator sites. Note increased craze density around 200 m/s impact sites (Figure 53). The initiator sites are small enough that by themselves they are not cause for removal. As with the dust erosion results, the water impact data suggest that a durability test spectrum for craze resistance should include resistance to water impact damage.

To determine the actual minimum craze for specific water impact velocity and damage would require modifying the location of impact sites, or the amount of load applied, on individual beams so that impact sites would exist at different stress levels than those used for this program. An increased number of impact sites could also be located on each beam, reducing the distance between the sites and increasing the resolution for determining the minimum craze stress.

3.5. Correlation of Phase III Results

Because the objectives of the service-aged coupon test matrix and artificially-conditioned coupon test matrix were different, formal statistical correlation of results were not attempted in Phase III. Inferred correlation was attempted with minimal success. For instance, both water and dust erosion exposure created barely visible damage which decreased craze

Table 10. Minimum Stress to Craze for Water Jet Impact Specimens.

Sample ID	Stress at Craze Front (psi)	Stress at Crazed Impact Site (psi)
R-201	1310	
R-202	1550	
R-206	1789	
R-301	1689	1689
R-302	1452	1056
R-304	1357	
R-401	1369	1043
R-402	1414	
R-403	1247	1032
R-501	1422	1034
R-502	1422	1034
R-503	1684	1684

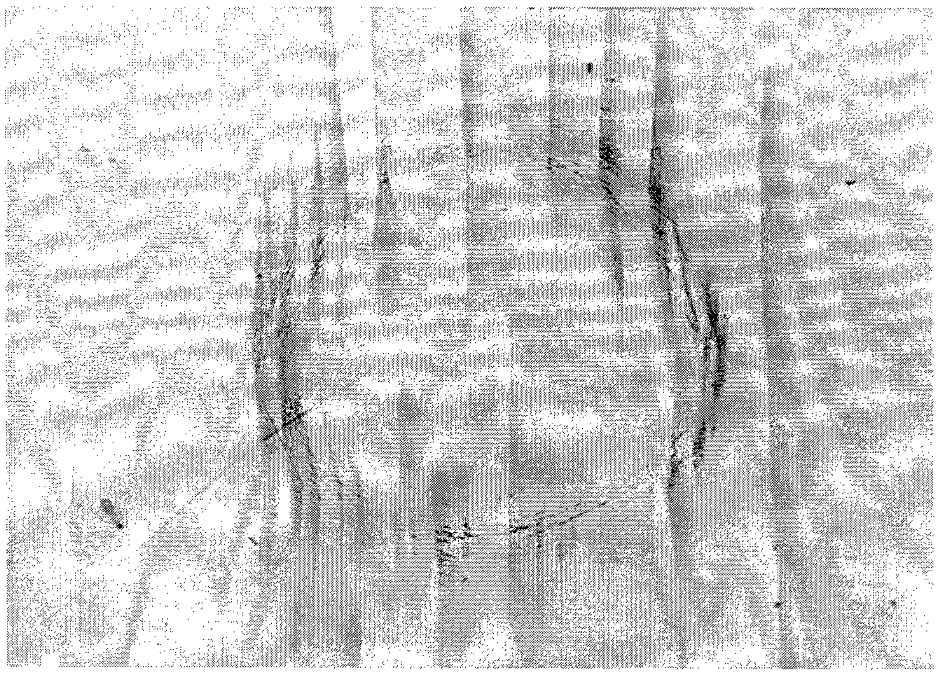


Figure 52. Craze Formation Water Impact Sample #401 (300m/s) (Magnification 100x).

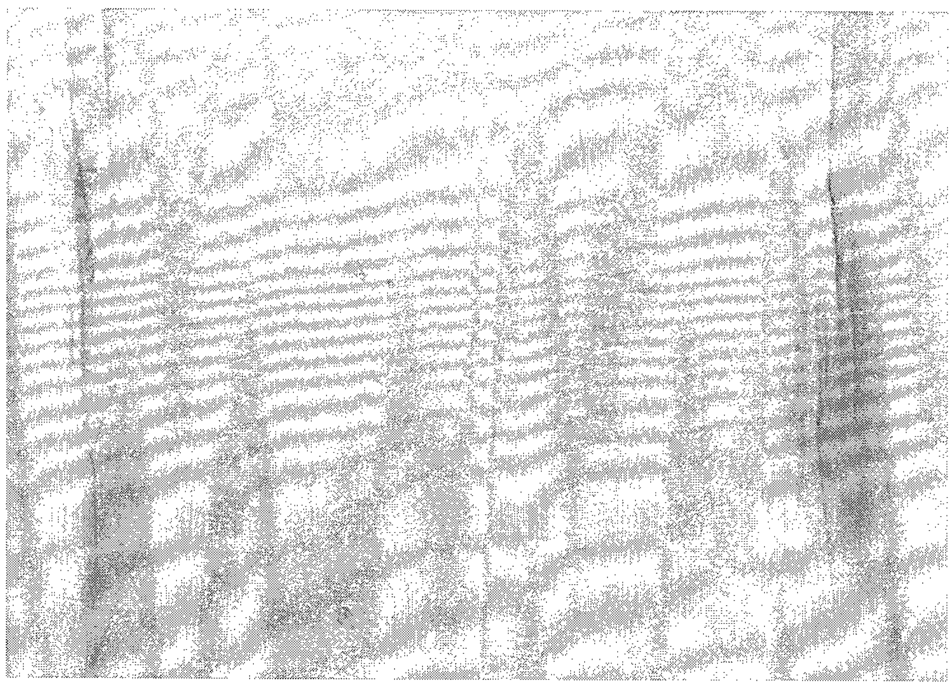


Figure 53. Craze Around 200 m/s Impact Site (Magnification 200x).

resistance in conditioned samples. If coupons from geographic locations exhibiting dusty or rainy conditions showed similar decreases in craze resistance, then a positive correlation could be inferred between simulated dust and rain exposure and service-related exposure. However, the data from service-aged canopies showed no identifiable decrease.

3.6. Conclusions from Phase III Results

The test results from Phase III service-aged coupons showed no discernible trends in any of the test parameters (hardness, density, craze resistance, UV transmission, infrared transmission, chemical make-up) as a function of environmental parameters (geographic groupings, total radiation, maximum temperature, total degree days, number of rainy days, and number of clear days). The manner in which changes in test parameters are tracked, by averages of absolute values and not changes in values from the baseline, is one reason for the lack correlation. Another is the lack of data indicating the true nature of the environment to which a transparency is exposed. It is clear that nondestructive methods for testing transparencies prior to installation (baseline measurements), and methods for tracking environmental conditions surrounding transparencies during their service life, are absolutely critical for defining a life-predicting durability tool.

Test results from Phase III artificially conditioned coupons showed clear and identifiable decrease in craze resistance of cast acrylic with dust and water drop impact. The damage resulting from dust or water impact is often not visible, or just barely visible, with the naked eye. Materials or coatings which are sensitive to microscopic damage may show good craze resistance in laboratory tests prior to dust or waterdrop impact, but may be actively flying on windshields in a damaged condition, increasing the risk for failure due to craze. The results suggest that an erosion evaluation of new materials to improve the determination of resistance to craze should be a part of any durability test spectrum.

It should be noted that sanding and polishing as part refurbishment of acrylic faced transparencies may remove rain and dust erosion damage, resulting in a surface which is essentially new. Refurbishment which does not include sanding and polishing of the forward facing portions of a transparency would not remove rain and dust damage zones. The service life of "refurbished" transparencies which did not undergo sanding and polishing would be expected to be shorter than that of a new part.

4. Field Service Data Acquisition and Data Analysis

The collection and analysis of field service data is critical to the understanding of the actual performance of aircraft transparencies in the field. Accurate field service data is essential for not only understanding the durability problem, but also for the development of coupon scale durability testing.

In Phase III of the Transparency Durability Test Criteria Program, UDRI analyzed data collected by Texstar, Inc., on F-16 forward canopies removed from the field [5]. As part of the Texstar, Inc., "Strip and Recoat" program, all F-16 canopies removed from the field are sent to Texstar and inspected for the possibility of refurbishment. As part of the inspection of each canopy, data such as Date of Manufacture, Serial Number, Base at Removal, Date of Removal, Manufacturer, Primary Removal Cause, and Secondary Removal Cause, are recorded and transcribed into an electronic database. (Note that the removal causes, or "failure modes," are those noted by the inspectors at Texstar and not necessarily the actual reason for removal which the field crews would have cited). The data collected in the Strip and Recoat Program are likely the most complete and consistent used to date in the UDRI program. All canopies are thoroughly examined under strong lighting by two individuals. The same individuals perform all of the inspections [15].

Under agreement with Texstar and OO-ALC, Hill Air Force Base, UDRI was provided canopy data from inspections through September 1994. UDRI added these data to the currently existing F-16 database and conducted a statistical analysis similar to the Phase II analysis [16]. Data was categorized and grouped according to manufacturer, type of coating, and model type (F-16 A/B/C/D). Rather than categorize "Air Force Base at Removal" according to broad geographic locations, actual weather data from base locations was compiled. Canopy failure data was grouped not by the location of the base, but by factors such as UV levels, average number of clear days, average number of degree days (used in analyses of heating requirements), maximum monthly temperature, and yearly rainy days. Pooling the data according to exposure conditions which may actually affect durability was considered an improved means of identification of trends than simple geographic grouping.

As in the Phase II Field Data Analysis, the primary statistics of interest in the Phase III analysis were "Proportion of Failures" and "Average Service Life," both as a function of failure mode. "Proportion of Failures" answers the question, "How do canopies fail?" "Average

Service Life" answers the question, "How long do canopies last?" Both are important for developing a durability methodology which addresses the most critical failure modes. Analyses were conducted for those groups (manufacturer, coating type, and model type) in which sufficient data existed to make an analysis within each group reasonable. Groups were combined if insufficient data existed and the data indicated that such combinations were reasonable. Analyses were not conducted for groups with insufficient data.

A number of conclusions were drawn from the analysis. While the canopies from the two manufacturers (Sierracin and Texstar) had significantly different proportion of failure modes, the average part-lives for each of the failure modes were not statistically different, except for polycarbonate cracking. In fact, pooling all data, part-lives of the two manufacturers are nearly identical for all years of manufacture except 1989 and 1990.

Another significant finding is that part-lives for a specific year of manufacture cannot be determined accurately unless all or nearly all of the parts from that year have failed and are included in the database. If the total number of manufactured parts for a given year were known, estimates of part-life could be made prior to failure of all of the parts. Based on 1984 to 1987 data, the average part-life for a laminated F-16 canopy is between 36 and 46 months. Part-lives for canopies manufactured after 1987 are shorter due to the fact that all of the parts from these years have not failed.

Analysis of the effect of weather parameters on part-life showed two consistent trends: 1) canopies in sunny, clear climates have shorter part-lives, and 2) canopies in areas with colder winters have longer part lives.

One known shortcoming of the database is that cracking of the polycarbonate at the edge attachment actually is much more common than indicated by the database. The reason for this is that cracks at the bolt holes and at the edge of the canopies cannot be detected with the naked eye. These cracks are only detected by using an optical prism or by stripping off the protective edge attachment paint/sealant. When the canopies are inspected and the data are collected for the database, the only polycarbonate cracks reported are those which are very large. Canopies are then separated into those which are scrap and those considered suitable for refurbishment. The edge attachment sealant/paint is stripped from the refurbishable canopies. Any edge cracks and bolt hole cracks which cannot be drilled out are cause for rejection of the canopy. Unfortunately in the past, when cracks were found, these data were not added to the database.

A similar analysis of the Strip and Recoat data through 1995 was recently conducted by Lockheed-Martin under OO-ALC funding [17]. Although the objectives of the Lockheed analysis were different than UDRI objectives, the conclusions of the report are worth noting. The conclusions included the following: more Sierracin transparencies have been removed from service than have Texstar transparencies; Texstar does not have a problem with premature failure of their coating systems; the failure rates of the coating systems on Sierracin transparencies have increased steadily since laminated transparencies entered production for each of the three Sierracin transparencies analyzed in the study; service lives of Sierracin transparencies peaked about 1987, and have steadily decreased. While the decrease may be caused by the lack of long-lived transparencies in the database, Lockheed notes that the decrease happened about the time the coating cure process was changed from oven curing to UV curing.

5. Significant Program Developments

Along with the core durability test criteria development, a number of tasks were conducted on this program which led to significant developments in the field of transparency durability testing and analysis. The most significant advances are discussed in the following sections.

5.1. Alternate QUV Weathering Cycle

One of the most important parts of a coupon scale test program to evaluate durability is the choice of artificial weathering or conditioning techniques. Numerous researchers have concluded that outdoor "life" (without respect to any particular failure mode) and "life" due to accelerated weathering do not directly correlate. The scatter in natural weathering data is too large, and the interacting factors too numerous, for calculations of universal "factors" which correlate natural and artificial "life" for all materials and environments. However, it is usually possible to correlate the ranking of material performance in artificial conditioning to that in natural conditioning as long as the artificial weathering adheres to critical factors found in the natural environment. In the long run, given sufficient statistical data on natural weathering and sufficiently large safety factors, it may be possible to develop conservative "life" values for natural exposure on the basis of artificial and accelerated exposure.

For transparency materials, the important factors include the spectral distribution of the sun's EM radiation, particularly in the UV region, temperature, and wet time (which includes dew condensation and is distinctly different from total precipitation or humidity of the air). Also important is the manner in which these factors vary on a daily basis over the course of a year. As part of the Phase I core durability test criteria effort, UDRI reevaluated artificial weathering techniques used in the past in an effort to identify or develop a technique which has the following attributes: simple to operate, lab scale, commercially available, accelerated, reasonable cost, UV spectrum which is similar to UV in the atmosphere, moisture included, and thermal environment of the transparency simulated as much as possible [1].

The evaluation showed the QUV to have a number of advantages over other laboratory scale weathering systems. The QUV is readily available and is inexpensive to purchase and to operate.. Virtually all of the major transparency manufacturers have QUV machines at their facilities. The QUV can duplicate periods of high UV exposure and temperature and low

moisture content, followed by periods of low UV exposure and temperature and high dew condensation. UV, temperature, and moisture (wet time) can be varied independently.

The artificial weathering profile for the QUV was developed by defining specific operating values for UV, temperature, and wet time, based on natural weathering data taken at two locations: New River, Arizona; and Miami, Florida. The former represents a location with high temperature and UV exposure. The latter experiences lower UV doses, but significantly higher wet times. The basic approach, common to all three environmental parameters, was to examine data collected by DSET Laboratories at the above mentioned geographic sites and reduce the daily data for each factor to a weighted average over a year's time. The weighting was dependent on the factor being considered and how it was perceived to affect polymer degradation. Specifically, monthly averages were calculated for 4 to 7 (depending on the environmental parameter) of the most recent years for which complete monthly data were available for at least 10 months. Using these monthly data, a weighted average was calculated for each parameter, giving a final yearly average of the parameter. These values were then correlated to QUV output measurements (Figure 54) to calculate cycle times and temperatures which would produce an equivalent year of wet time in Miami and an equivalent year of UV exposure and temperature induced degradation in New River. QUV cycles could therefore be considered "worst case" by combining the most damaging environmental effects from each location.

Two models were developed to simulate temperature induced degradation. Both models yielded equivalent QUV temperatures in the range of 70°C to 75°C. Concerns about difficulty in correlating failure data from the field to severely overexposed specimens lead to a conservative approach to selecting exposure temperatures. A QUV temperature of 70°C was selected based on the overexposure concerns. Note also that dark/wet temperatures are often lower than light/dry temperatures, further preventing overly severe exposure. The complete QUV cycle developed in the program is 16 hours of UV exposure under UVA-340 bulbs, followed by 8 hours of dark/condensation, all at a temperature of 70°C. Based on simplified proposed models, the 16/8 cycle conducted continuously for 8 weeks should roughly match the degradation due to 1 year of UV radiation energy (300-380 nm) and temperature in New River, Arizona, and the average percentage wet time in Miami, Florida.

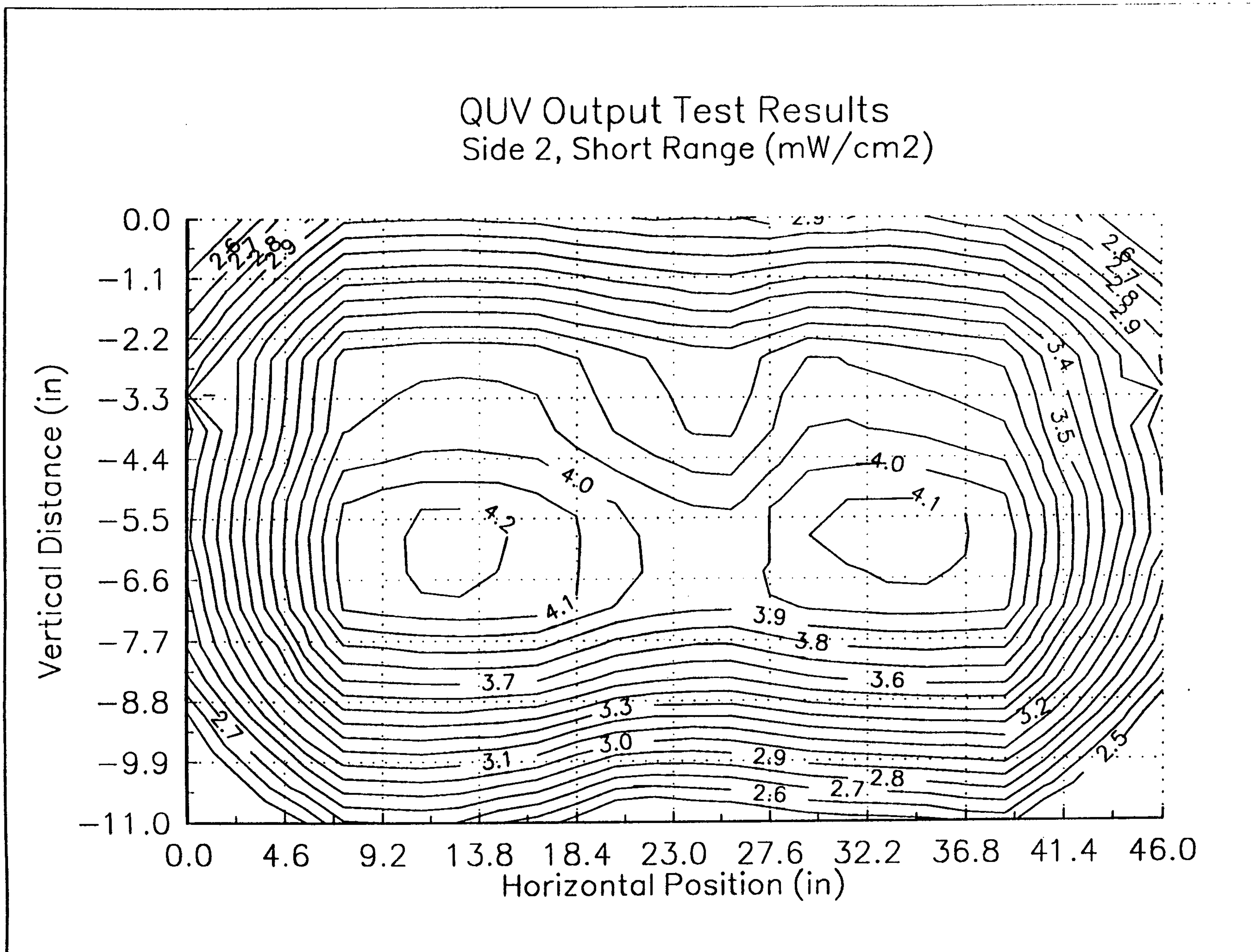


Figure 54. Measured Output of UVA-340 Bulbs in the 300-380μm Wavelength Band.

5.2. *Dust Erosion Test Methodology*

The Dust Erosion Test and Analysis Facility was developed for the Defense Nuclear Agency and has been in use since the early 1980's to evaluate high-speed dust abrasion of a variety of materials. Materials which have been evaluated include transparency materials for aircrew enclosures, infrared (IR) transparent materials, coatings, and paints. Pitot tube clogging also has been evaluated using this facility. The facility can be used to assess the effect of particle velocity, particle mass flow rate, impact angle, and exposure time on erosion response. This test facility has been accepted as the test standard for the IR materials community.

The dust erosion facility was shut down when the Engineering Services Division of PDA Engineering (the operator of the facility) was dissolved. The Aircrew Protection Branch of the USAF Wright Laboratory Flight Dynamics Directorate recognized the need within the transparency and IR communities to keep a dust erosion test resource available. The facility was relocated to the Flight Dynamics Directorate in October of 1994. The facility is currently housed in the Transparency and Thermal Systems Laboratory, Building 45A, Wright-Patterson AFB, OH. With relocation, setup, and test validation completed, the facility is again available to meet the testing needs of the transparency community.

The University of Dayton Research Institute (UDRI) set up, calibrated, and validated a test methodology for the dust erosion facility at the new location [13]. The setup and validation process consisted of assembling subsystem components into a fully operational system, verifying and documenting operational procedures, and validating the operation of the system by duplicating previous test results. WL/FIVE-1 and UDRI personnel participated in the setup of the facility, are familiar with facility operation, and are qualified to conduct testing in the facility. The procedures for operating the facility did not change significantly when the facility was relocated. None of the essential equipment was replaced or modified, with the exception of a new nozzle and nozzle block which were fabricated according to engineering drawings and specifications which accompanied the facility.

The Dust Erosion Test and Analysis Facility is fully operational with dry air as the transport gas. A large supply of bulk crushed silica sand is available for sieving to desired particle size distributions. The facility currently possesses the following operational capabilities:

· velocities to 320 m/sec

· particle sizes from < 38 micron to 177 micron

· mass flow rates from 0.02 to 20 g/min

· specimen sizes up to 6 inches square.

A number of additional facility capabilities were developed by PDA Engineering which incorporate features to conduct specialized testing. However, these capabilities are not currently operational. Additional effort would be required to assemble and validate the components. The specialized capabilities not currently operational include low temperature exposure, dust exposure and clogging of pitot static tubes, and ultra-low flow (< 1 psi nozzle pressure) exposure using nitrogen.

A series of validation tests was conducted to demonstrate that the facility was operating in a manner similar to that established when it was located at PDA Engineering in Costa Mesa, CA. The test series consisted of soda lime glass samples exposed to conditions for which previous data were available. Comparisons to previous data were made to assess the operating condition of the facility. IR material samples were also exposed for the purposes of developing a Dust Erosion Test Method (Figure 55). The proposed method has been submitted to the American Society of Testing and Materials (ASTM) Subcommittee F07.08 for consideration as an officially sanctioned ASTM Test Method.

5.3. Aging of PVB/Glass Laminates

There have been two catastrophic in-flight failures of KC-135 celestial navigation windows: one in 1974 and one in 1988. Each of these failures has resulted in rapid decompression of the aircraft and a fatality. The window is a 13-inch x 15-inch glass/PVB/glass laminate. No information was obtained regarding the failure of the first window in 1974. The cause of the glass ply failure was unknown for the 1988 failure; however, the cause of the failure of the fail-safe PVB ply was determined to be PVB degradation and subsequent fatigue cracking of the PVB at the periphery of the window. In 1974 an engineering change was made to the window, which consisted of changing the bumper from PVB to a sealant and covering the PVB at the edge attachment with a sealant. Both transparency failures were the pre-1974 design.

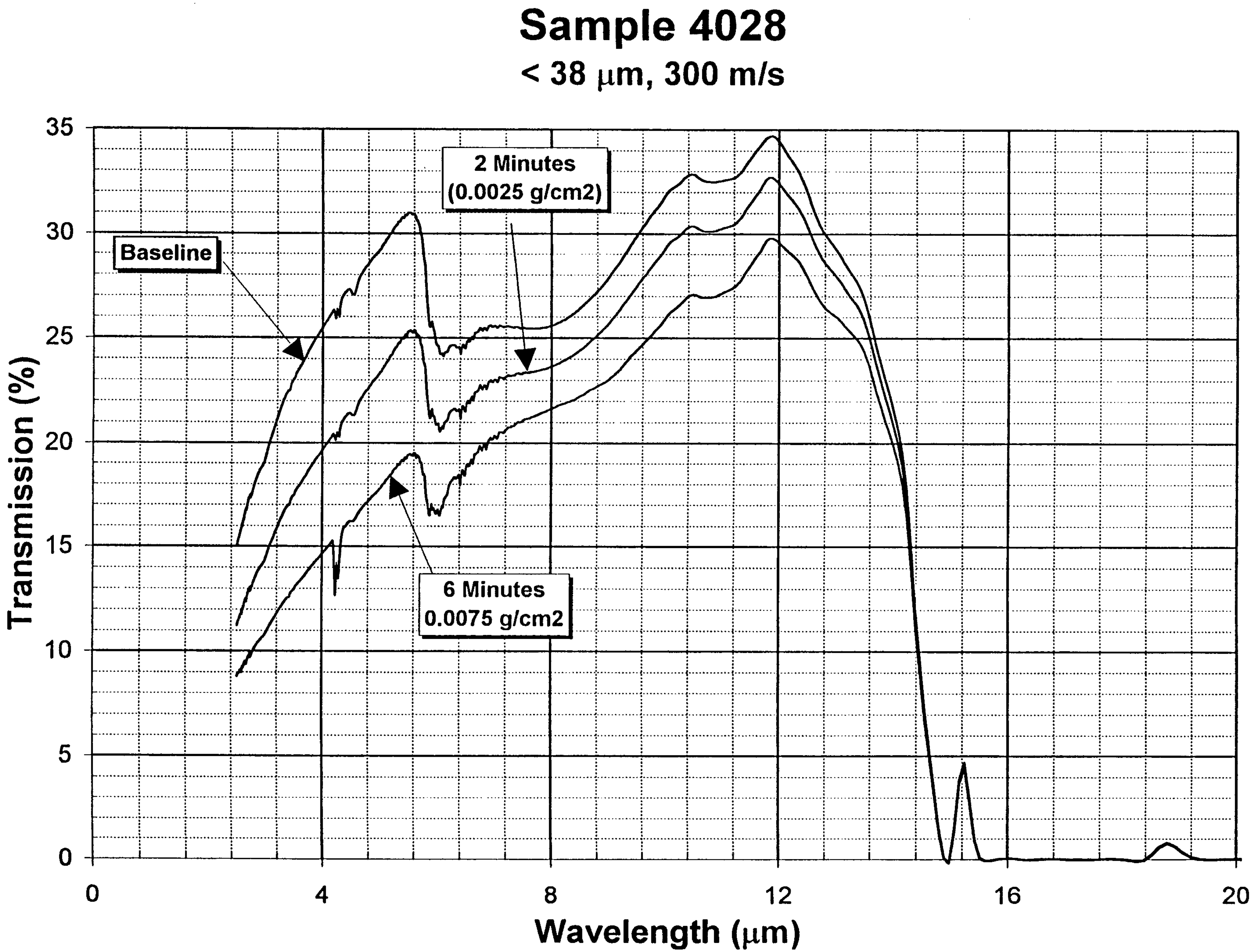


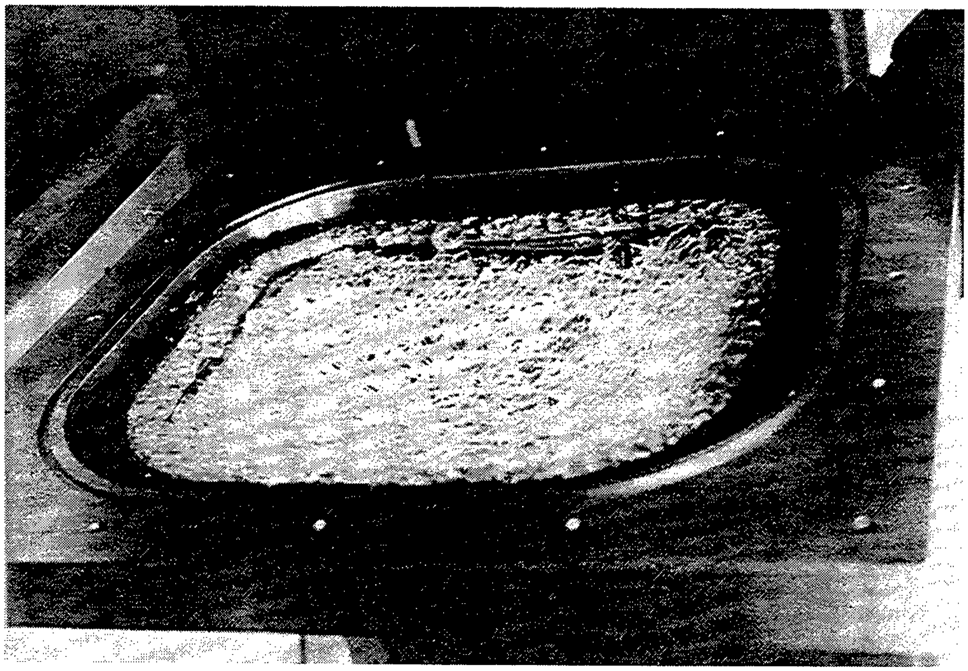
Figure 55 Reduction in IR Transmission of Coated ZnS Due to Dust Erosion

During the life of the KC-135, celestial windows have been removed and replaced only if they no longer met the optical requirements. There was no requirement for removal and replacement after a given structural service life. As of 1991, the average age of the cargo/tanker fleet was 23 years. The average age of the KC-135 fleet was over 27 years. The celestial window failures coupled with the high average age of the fleet have led to general concerns over the effects of aging on interlayer materials' resistance to degradation. Numerous aircraft with transparency system designs containing PVB interlayers could be subject to similar failures.

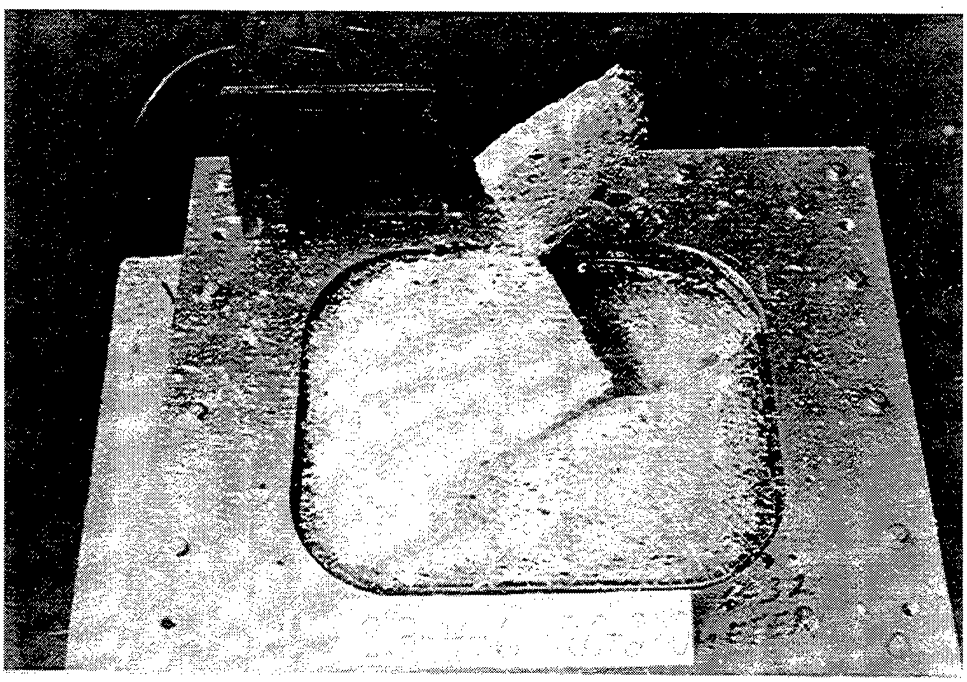
In December 1988, for flight safety reasons, the interior surfaces of the celestial windows were covered with an aluminum skin to prevent additional failures. Also, a directive was issued to remove the celestial windows and replace them with an aluminum plate as plates became available. Although effective, a more satisfactory preventive measure would be to develop a removal for cause criteria that involves age of the transparency. Transparencies that otherwise appear sound upon inspection would be replaced when the criteria is met. Given such a criteria, the methodology for developing the criteria can be applied to other transparency systems.

The KC-135 celestial navigation window was identified as a focal point for developing a removal for cause criteria. UDRI conducted a test program to provide technical and testing support for this aging study of KC-135 celestial windows [18]. The objective of this work was to contribute to the development of a removal for cause criteria for the KC-135 celestial navigation window by investigating (through testing) the relationship between service-age and interlayer burst strength. The testing conducted in this program included pressure proof testing of the celestial window and burst testing of the PVB interlayer (Figure 56). Included in the program was development of a suitable test system which could be modified to test other transparency systems. Statistical analysis of the data was performed to estimate 99% confidence intervals and extrapolate a lower age limit below which burst failure would not occur.

A risk analysis was conducted following MIL-STD-882C, Military Standard for System Safety Program Requirements. A removal for cause criteria, based on burst test data, a 10 psi maximum cabin pressure, and a 0.05% Failure Risk level, would require replacement of the window after 10.5 years of service-age had elapsed. A planned changeout of 10.5 years



Specimen 6-H-11-9-12. Typical Edge Tear During Fail-Safe Test.



Specimen 83-H-6-20-210. Typical Complete PVB Tear During Fail-Safe Tests.

Figure 56. Burst Test of KC-135 Celestial Navigation Window.

represents a considerable reduction in risk compared to current optical criteria, which may have windows in service for 25 years or more.

It should be emphasized that the PVB in the KC-135 windows provides a fail-safe component for the windows. If the glass fails, the PVB is supposed to maintain structural integrity and hold cabin pressure. The testing in this effort provides evidence that there is a limited lifetime to this fail-safe protection. It is recommended that service life be limited for this type of window. Other similar windows should also be investigated.

5.4. Durability of Coatings

In the past cast and/or stretched acrylic provided satisfactory service life and performance for the exterior of aircraft transparency systems. However, current and future requirements for rain erosion, abrasion, and chemical resistance, as well as electrostatic discharge (ESD) protection, radar cross section (RCS) reduction, and directed energy protection, are dictating the use of coating systems on the exterior of aircraft transparencies. Another requirement which has resulted in the need for external coating systems is the birdstrike requirement. Optimized birdstrike protection often requires the use of monolithic or laminated polycarbonate. Polycarbonate must be protected from the environment with a coating. Coatings themselves can be complex systems consisting of a variety of basecoats, tiecoats, conductive layers (metals, metal-oxides, and doped organic materials), and top-coats. Each of these individual portions of the coating system provide potential failure zones in terms of both performance and durability. The coatings may become hazy, delaminated, pitted, or removed due to the individual or combined effects of abrasion, rain erosion, chemical attack, weathering, and other factors.

In addition to the aircraft crew enclosure, other aircraft transparencies frequently require the use of coatings to provide acceptable performance and durability. Examples include the various aircraft sensor windows and pilot visors.

As part of this program, UDRI evaluated a number of transparent coating systems for pilot visors. The specific intent of this effort was to test, transition, and utilize crew enclosure transparency coating technologies to increase durability of coated polycarbonate pilot visors. Evaluation included abrasion, weathering, adhesion, and ballistic testing [19].

5.5. Improved Bolt Hole Durability

Aircraft transparencies must provide reasonable performance and durability with acceptable life cycle costs. The single most important performance parameter is flight safety. The two modes of transparency failure which affect flight safety are transparency failure due to operational flight loads and transparency failure due to impact with a bird. For transparency systems which are attached to the aircraft with bolts, these two potential failure modes are extremely dependent on the condition of the bolt holes. Cracked or flawed bolt holes greatly reduce the fatigue life of the transparency and the resistance to dynamic loads induced during flight or from birdstrike. Inspection of service aged transparencies has shown that F-111, F-16, and B-1 transparencies frequently have cracks and other flaws at bolt hole surfaces in the edge attachment. Other new systems which may be affected in the future include the F-15, F/A-18, B-2, and the F-22. Improving crack and flaw resistance of bolt holes in aircraft transparencies like these results in a reduction of risk of transparency failure. An additional benefit of improving crack and flaw resistance of bolt holes is that bolt hole cracking as a removal-for-cause failure mode can be nearly eliminated. Improved durability bolt holes have tremendous potential for extending not only the initial life of aircraft transparencies, but also in extending the refurbishable life of a transparency. Improved bolt hole durability would reduce the number of cracked fastener holes and would thereby increase the number of parts which could be refurbished. This results in a reduction of life cycle costs since refurbished transparencies typically cost only 60 percent of what new transparencies cost and have similar service lives to new transparencies. In addition to extending the service life, the reduced number of bolt hole cracks would result in stable bird impact capabilities for the transparencies, since cracked fastener holes have been shown to cause a reduction in bird impact capability [20].

UDRI first conceived the need for and potential solutions for improving aircraft transparency bolt hole durability. Work at UDRI showed that improvements of as much as a factor of 10 could be realized by cold working polycarbonate transparency fastener holes [21]. UDRI continued that work under this contract and under F33615-92-C-3400 by optimizing the parameters associated with cold worked fastener holes and fastener holes with interference fit bushings.

The cold working technique involves pushing an oversize (10 to 14 percent) tapered pin through a drilled bolt hole. Because the pin is larger than the hole, the pin causes both elastic

deformation and plastic deformation (yielding) around the hole as it is pushed through. The elastic deformation is recoverable, but the plastic deformation is not. Recovery of the elastic deformation forces the plastically deformed portion (closest to the surfaces of the hole) to be in compression. This compression is permanent and results in improved fatigue resistance, since the compression stresses must be overcome before cracking can occur.

The interference fit bushing technique involves pushing an oversize (3 to 9 percent) bushing into a bolt hole. The interference fit causes elastic and plastic redistribution of stresses at the surface of the hole. This favorable stress field results in an improvement in fatigue life for the hole.

Work conducted as part of this program indicates that interference fit bushings may in fact provide even greater improvements in durability of bolt holes in polycarbonate aircraft transparencies than cold working. Figure 57 shows that for 0.150-inch-thick polycarbonate material, the interference fit bushings are showing an improvement in fatigue life of as much as a factor of 100 over drilled holes, and an improvement in fatigue life of as much as a factor of 10 over cold worked holes. In addition, interference fit bushings may be easier to implement into the manufacturing process with minimal cost and time impact. Additional work in terms of manufacturing process development and validation is required to transition these technologies to the transparency industry.

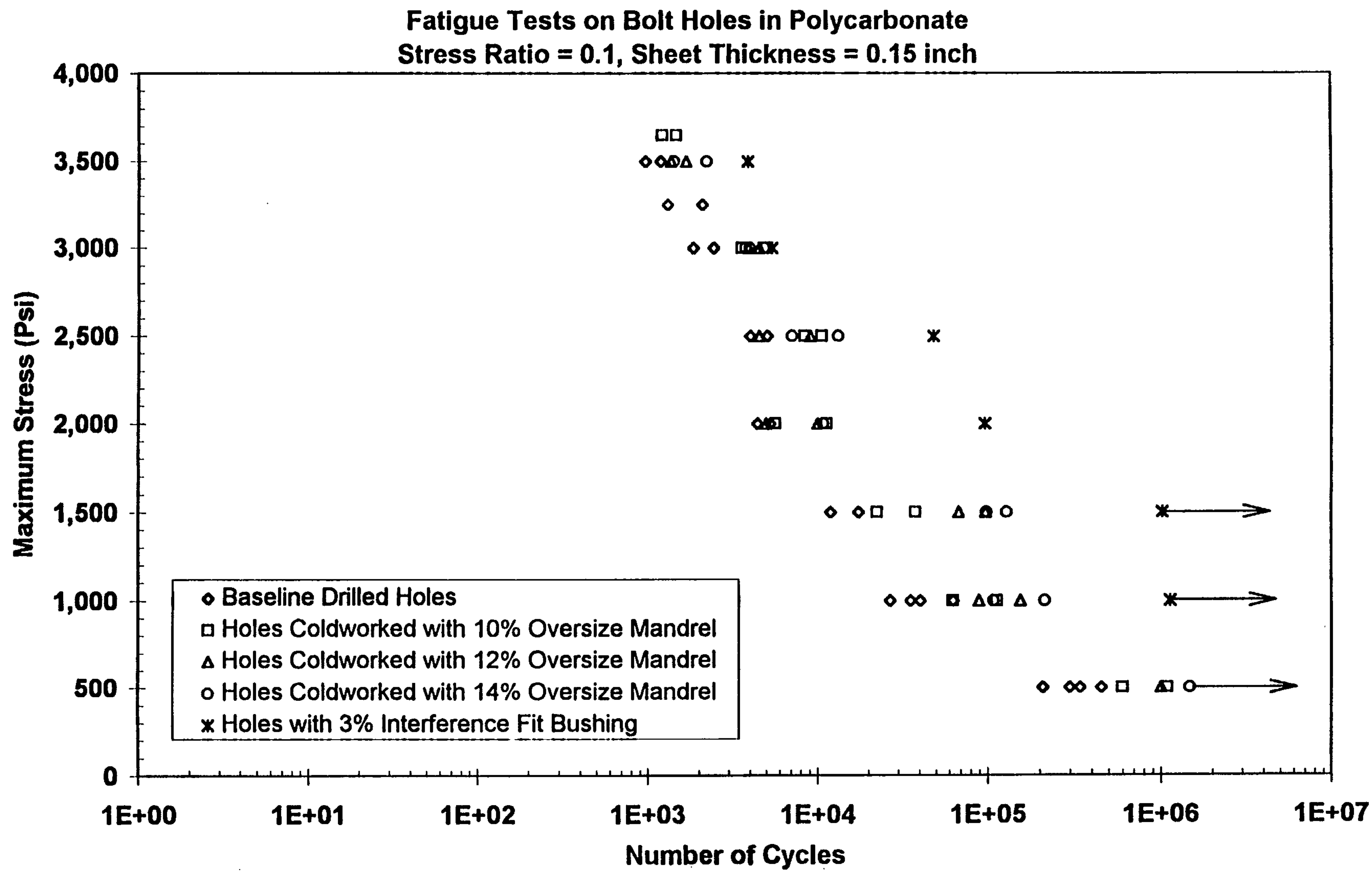


Figure 57. Improvement in Fatigue Life with Interference Fit Bushings.

6. Conclusions and Recommendations

6.1. *Identification of Technology Voids*

The original objective of the Transparency Durability Test Criteria Program was to predict transparency service life based on correlation of Field Service Data to coupon-scale and full-scale test data. The focus shifted, however, as the program evolved. Results indicated that insufficient information existed in several key areas which prevented meaningful correlation of data and durability prediction. The technology voids responsible for the poor correlation included the following:

Insufficient detail regarding the actual exposure environment of transparency systems. Documenting and correlating test results to general weather and atmospheric conditions does not give a complete picture of the circumstances surrounding transparency service life exposure or transparency failure. Improved methods for tracking and recording service conditions must be developed and used. Service conditions which must be documented are of two types: environmental parameters, such as temperature, radiation exposure, and humidity, which can be recorded by sensors mounted to a transparency; and unique, one-of-a-kind exposures, such as small particle impact, inadvertent chemical exposure, or maintenance damage, which perhaps cannot be recorded automatically and require documentation by hand. Both are important in interpreting failure data and correlating the data to coupon test results.

Need for Improved artificial weathering techniques. The current program has demonstrated that some failure modes are not reproduced by "standard" artificial exposure techniques. Data gathered through sensors and personnel reports must be used to generate improved exposure methods. The current program has demonstrated, for instance, that crazing is coupled to abrasion resistance, itself a "property" associated with abrasion failure. Durability assessment should include not only UV, temperature, and humidity as driving forces for chemical stress crazing, but also water drop and small particle impact, which can create barely visible damage sites which initiate craze.

Insufficient nondestructive test methods. The best way to track properties of a component over its service life is to test the component when it is new, prior to placement into service, and repeat the testing many times over the component's service life. Such a procedure is not possible for transparency systems, as current testing technology is primarily

destructive. A transparency can be tested only once during its lifetime, either before entry into service, rendering it unusable, or after some period of service, meaning no baseline data are available. Changes in test properties over time must be calculated by averaging data from several transparencies with similar service-history ("pooling" the data) and subtracting the average of different transparencies without service life ("baseline" transparencies). While one might assume that all "new" transparencies have similar properties, the current program has demonstrated that the spread in the pooled and baseline data is so broad that clear correlation and trends are difficult to identify.

6.2. Field Data Analysis

Along with identification of technology voids for improved durability prediction, the current program also provided the first comprehensive statistical analysis of available transparency field service data [16, 22, 23]. Data were collected through three primary channels: on-site inspection of failed transparencies at the bases at which removal occurred; inspection of failed transparencies at Air Force warehouse facilities; and through the inspections performed by Texstar, Inc., in their Strip and Recoat Program. Data were analyzed using two metrics: proportion-of-failures, which answers the question, "How do transparencies fail?"; and service-life, which answers the question, "How long do transparencies last?" Each metric was correlated to a number of factors, such as manufacturer; date of manufacture; transparency type; geographic location; weather conditions at the base of removal, and for service-life correlation, failure mode. The primary advantages of in-depth field data are its use in identifying the circumstances surrounding transparency service life and failure, validating the test methods used in assessing durability, and in identifying patterns in transparency failures, such as those failure modes which have the shortest service life and are therefore most troublesome. The field data analysis in the current program identified patterns in failures based on manufacturer and geographic location. The analysis was also used to direct the efforts of the Phase III coupon testing towards an often occurring failure mode for F-16 canopies: acrylic crazing.

While a correlation between field service data and coupon testing in the current program was difficult to identify, it should be realized that the field data analysis in combination with currently existing transparency procurement specifications provide a degree of correlation between the coupon test results and field service data. For instance, the F-16

Procurement Specifications requires 3000 psi acrylic craze resistance for 30 minutes with isopropanol after a battery of temperature, humidity, sunshine, and salt atmosphere exposures have been conducted. Assuming that manufacturing process control is such that the requirement is actually maintained, field data indicates that this test result corresponds to average service life for failure due to craze of 55 months for Texstar canopies and 58 months for Sierracin canopies. (However, the spread for individual canopies is quite large - from 4 months to 133 months - and is dependent on factors such as geographic location.) While this association is a start, it is only a single data point with a handicap: it is a preproduction requirement and not a requirement that is tested on every canopy. To extend the association would require one of two approaches: obtain baseline test data for each transparency that entered service, data on service history, and data on failure mode; or increase the performance requirement and determine what effect the increase has on service life. The first is a preferred approach but will require advances in testing techniques and in-service data collection. The second is unlikely to happen since it would require new materials and re-qualification and it is a poor approach if the underlying association between laboratory testing and field exposure is not understood.

6.3. Other Approaches to Improve Durability Assessment

The results of the program have identified specific issues which must be addressed for durability assessment techniques to advance. The issues were summarized in Section 6.1. Other approaches also exist for improving durability assessment. The following items should be considered for investigation or implementation to compliment existing efforts.

Implement a risk-based assessment of durability. With the myriad of variables involved in durability assessment, it may be more appropriate to talk in terms of failure "risk" than in terms of an actual prediction. For instance, based on coupon testing, a transparent material has a certain probability of failure for each level of exposure to some "factor." In the field, a certain probability exists that a transparency will experience each of those levels of exposure. A statistical "convolution" of the probability curves will yield a "risk" that the transparency will fail due to that factor. This approach is similar to the risk assessment performed for KC-135 celestial navigation windows [18] and has the advantage of accounting for the manner in which data is distributed. Such information is lost when dealing strictly with averages. As with any assessment, however, implementation will depend on accurate understanding of the exposure

environment, accurate replication and acceleration, and use of test coupons which simulate the actual component.

Develop nondestructive or accelerated destructive tests to transition procurement durability assessment from preproduction tests to acceptance tests. Durability assessment currently is conducted only in the course of vendor qualification. The ideal situation has the vendor nondestructively testing the durability characteristics of each transparency as it is fabricated, or destructively testing a production article at regular intervals to check for processing accuracy (statistical methods exist for the appropriate number to test and the appropriate interval). The requirement for nondestructive testing has already been discussed. Material suppliers and fabricators in many industries regularly conduct destructive testing on production parts to ensure quality control. However, destructive testing does little good if durability assessment, such as QUV weathering, takes weeks or months to complete. Accelerated tests, for which clear interpretation of test results exists, must be developed if durability assessment is to be conducted on a regular basis.

Implement quality control procedures at the vendor such that process controls are related to the results of durability assessment tests. What can be done to improve durability assessment if the nondestructive tests described above never materialize? One possible course of action is to characterize the "robustness" of the fabrication process. It is possible that the fabrication process must be controlled to a very high degree to maintain the durability resistance to which the vendor originally qualified. In the absence of durability acceptance testing, fabricators can, at a minimum, understand how process controls affect durability test results. Given that knowledge, the Air Force can be assured of the durability resistance of the parts being produced based on QC documentation that the process is adequately controlled. Process control may have the added benefit of relieving the durability assessment "ideal" of baseline data for each transparency produced by reducing the amount of scatter in the data. Process "robustness" evaluation will require destructive testing of new production transparencies for each of a number of small but controlled changes in process parameters. Statistical and sampling techniques exist for performing robustness testing in a controlled, structured manner [24].

"Robustness" studies must also include characterization or variations in material as received from the supplier. It is critical that variations in physical and mechanical properties which affect durability and still meet mil-spec material requirements be completely understood

so that baselines in robustness studies can be established. Lot-to-lot variations in material, if not identified and controlled, may be incorrectly identified as random variations in transparency manufacturer processing.

In whatever form future durability assessment is conducted, the issues discussed in Section 6 should be seriously considered, particularly the involvement of the material vendors and transparency fabricators. If a true predictive or risk assessment capability is to be developed, the capability will depend on knowing the true durability capacity of the component in the field. The vendors and fabricators have the best means by which to make that information available. To get a vendor involved will require convincing the vendor that doing so will help him competitively. Involvement of ground crews and maintenance personnel will also be required if good, accurate service histories are to be obtained. As with the vendors, ground crews and maintenance personnel (or their superiors) will require convincing that active participation in data collection will ultimately result in a more durable transparency requiring less of their attention and resources.

7. Reviewer's Comments

The intent of the Transparency Durability Test Criteria (TDTC) effort was to lay the ground work for a test technique by which to evaluate durability. While it is beyond the scope of the effort, the data presented and developed in this and other TDTC reports could be used to judge the status of transparency durability with regard to specific durability problems and efforts to solve them. Prior to publication of this report by the Air Force, the report was reviewed by a transparency industry expert and consultant [25]. His experience, industry knowledge, and reactions to the TDTC effort should be taken into consideration when using TDTC results to make such judgments. Major comments, in italics, are reproduced in the following paragraphs, followed by the author's reply in regular type.

With regard to Paragraph 2.1: *The report states that durability has been demonstrated on flat coupons but has been a problem on full scale. During informal discussion with OO-ALC/LFSM, two issues: first is where is the data to back up this statement, and second is that the F-16 specification requires coupon testing be done on samples cut from a full scale transparency. Has this been done and what is the result? One further comment - how have the data from the flat coupons been related to the full scale which are reported to have failed? This in terms of process control, process similarity, and very important, calendar time of the two events?"*

Authors' response: The "data" for this statement came from reference [7] and is anecdotal in nature rather than empirical, and meant to illustrate that laboratory scale coupons must duplicate the essential features of production components. The poor durability of coatings applied to full-scale contoured parts is evidenced by field failures and not by laboratory testing of full-scale parts. To the authors' knowledge, correlation of data from flat coupons to failure of full-scale parts in terms of process control, process similarity, and calendar time has not been published in the open literature. Details on vendor efforts to perform such correlation were not available at the time of publication and are usually treated as proprietary by the vendors.

With regard to Paragraph 2.3: *"First, you have to get a good, verifiable, qualification test matching the process used for full scale. Next you need a good set of acceptance test criteria. Thirdly, the acceptance testing and monitoring must be fully credible. Process changes can be deadly.*

"Finally, when we already know what the problem is, where it is, someone has to force a solution, or as in some cases, not get in the way."

Authors' response: The authors agree that such an approach is desirable. As detailed in Section 6.3, further improvements would include development of nondestructive testing to transition qualification testing (one-time test) to acceptance testing (test of every part or batch of parts).

With regard to Paragraph 3.2: *"It has been shown that an important part of the "environment" is the wash fluids routinely used by the AF. Some of these, particularly demonstrated at Shaw AFB when it was first activated, are very aggressive and collect under the edge fairing, subjecting the selection to long term exposure."*

"See also page 76 which omits the base effects. Historically, this has been one of the most important data issues. Recall 1980 and the infamous '90 hour life' of the first monolithic, a situation used by the F-16 SPO...to denigrate that design. The problem showed up at MacDill AFB and was the result of sulfuric acid generated by airborne output from nearby fertilizer plants. The coating did erode quickly under these conditions. If data from MacDill had been ignored, a different conclusion would have been possible. Maybe not a satisfactory solution, but a different, more tolerant one."

Authors' response: The reviewer's comments echo the authors' in Section 2.3 of the report, Methodology Validation: "Identifying the factor(s) which render durability testing inaccurate is like the work of a detective, following clues and gathering evidence that points to the circumstances for which durability testing has not accounted. 'Circumstances' include...lack of understanding of the environment itself..." Statistics, which can be used for effective screening and identification of factors important to a process, should not be used as a replacement for understanding the physics, mechanisms, and science of a phenomenon.

Concluding reviewer comment: *"It should be a continuing goal to understand the operating environment of the aircraft and to transform this into a suitable specification. However, for the F-16 there is no data to indicate that the current specification is inadequate except as it relates to ESD (Electrostatic Discharge). It is known that three programs are proceeding to resolve the issue. The F-16 issues are:*

a) Acrylic Cracking - Texstar thinks they fixed it.

b) *Sierracin coatings* (authors' note: Sierracin is changing curing processes to fix the problem).

c) *Sierracin edge cracking - if what you report about adhesives is true, this information was available in 1977, AND well advertised* (authors' note - Sierracin has solved this problem).

d) *ESD - being worked by LFSM, FIVE, and Pilkington Aerospace, Inc.*

e) *Edge sealing - inadequate sealing and wash fluids create failures.*

Authors' response: "Adequacy" is a relative term and depends on the level of performance required by a system. If the goal of the Air Force is to procure transparency systems with a minimum life expectancy of four years, the spec is inadequate based on field data which indicates a service life of 4 to 13 months [23]. If the distribution of service life represented by these data is acceptable, then the spec is adequate. It must be realized, however, that the durability "picture" reflected in a 4 to 133 month service life distribution might be incomplete, since anomalies such as the "sulfuric acid case" noted above may exist in the data.

The authors agree that the F-16 issues delineated above represent the priorities for the Air Force concerning the F-16 transparency system.

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